Optimization and Characterization of an Inkjet Process for Printed Electronics

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Optimization and Characterization of an Inkjet Process for Printed Electronics

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ABSTRACT

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Optimization and Characterization of an Inkjet Process for Printed Electronics

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Printed electronic fabrication processes have received much attention in recent years due to its potential applications in creating affordable, flexible, low-waste, and diverse electronic devices. The Fujifilm DMP-2830, a compact inkjet material deposition system new to the electronics fabrication labs at Ohio University, is explored and optimized in this thesis by printing two silver nanoparticle inks on glass, photopaper, and PET substrates. A systematic approach toward the characterization of the two nano-inks and common substrates as well as test devices is provided to develop useful fabrication recipes for future users of the DMP-2830. Various designs of resistors, capacitors, and inductors are fabricated on glass, photopaper and PET. For each test device, effects of process and geometric parameter changes were studied. Two sensor applications were also demonstrated to indicate the potential of inkjet printed sensors for future research. The first sensor was a resistive bend sensor to sense motion/deformation, and the second was a capacitive wax microfluidic sensor with a novel printed fabrication approach. It is believed that the methods employed in the characterization of nano-inks and devices in this thesis can be emulated by other materials and substrates in the future when the DMP-2830 is utilized to print a wide range of advanced sensors and devices.
DEDICATION

I offer this work to Almighty God the Father and my family who have guided me through life with unwavering love, compassion, and support.
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CHAPTER 1: INTRODUCTION

This thesis is focused on the optimization and application of the Fujifilm Dimatix Materials Printer (DMP) 2830, a benchtop drop-on-demand (DOD) inkjet printing system oriented toward rapid prototyping. The introduction of this thesis will first present the motivation for investigating new fabrication techniques, specifically inkjet printing. Second, fabrication and complexity of silicon semiconductor devices will be reviewed. The third objective of the introduction is market validation of an existing and growing market for inkjet printed devices. Fourth is an orientation to the materials and substrates that prove inkjet printing has meaningful purpose in device fabrication. To conclude the introduction, the goal of this thesis is stated.

1.1. Motivation

The availability of functional materials as commercial inks, and the constant demand for versatile, affordable, and creative technology has driven research in inkjet printed electronic devices. Along with these driving factors, the printing of functional materials is appealing to engineers and designers due to the rapid prototyping characteristic that inkjet printing offers [1] [2] [3] [4]. It has also been estimated that inkjet printed sensing devices will be 1/10th to 1/100th the cost of conventional sensing devices [5]. In this thesis, the DMP 2830 benchtop DOD printing system, commonly used to explore fabrication of printed electronics, is chosen to print both small and large area prints with drop spacing as small as 18 um and minimal feature sizes approaching 50 µm. Compared to screen printing and capillary action printing techniques, inkjet printing with the DMP 2830 encompasses very large middle ground in feature sizes where small and large features are down to 38 µm and up to 300 mm. Inkjet printing is an additive process that promotes printing of functional materials with less waste and lower cost without the need for large manufacturing real estate; most materials and patterns may be printed with the same machine [6] [7]. The Fujifilm DMP 2830 has been used to print a wide range of inks from organic semiconductor materials to conductive metal nanoparticles by changing the ink cartridge and
performing print head calibration promoting rapid deposition of many functional layers [8] [9] [10] [11]. The work in this thesis focuses on the optimization of two silver nanoparticle inks and three substrates. Along with the optimization of these materials, fabrication and characterization of inductors, capacitors, and resistors is completed on all three substrates, and fabrication of passive sensing devices on two substrates is demonstrated.

1.2. Traditionally Fabricated Electronics

Fabrication of silicon semiconductor devices is a demanding process that requires a multitude of complex machines, chemicals, and large manufacturing footprint. The process of fabricating a silicon semiconductor device begins with a “wafer” of extremely pure silicon which, in and of itself, has a meticulous preparation process to ready the wafer for fabrication [12]. From this point on, fabrication is performed in a clean room where the climate is monitored, and dirt, dust, and other foreign contaminants are kept out. The wafer is then etched with strong acids, such as hydrofluoric acid, to remove the thin silicon dioxide layer and reveal the underlying silicon. Thermal oxidation or deposition is performed to form a controlled layer of silicon dioxide. The wafer is then ready for masking which is used to pattern the wafer. This process is referred to as photolithography. Patterns on the mask are formed on the surface of the wafer by using a mask aligner to expose photoresist, a light-sensitive material, to intense ultraviolet radiation. The mask patterns individual “chips” as well as the chips’ components on the wafer. Once patterned, the wafer is developed, and the desired pattern without developed, hardened photoresist is etched with a chemical solution or plasma [13] [14]. The next step is doping the wafer with impurities. Intrinsic silicon has electrical properties that lie somewhere between conductor and insulator. To alter the intrinsic silicon to act as conductor or insulator, doping is performed. Doping is when the wafer is implanted with other atoms, such as column V donors (n-type, one more valence electron than silicon) or column III acceptors (p-type, one less valence electron than silicon) [15]. The dopants modify the intrinsic semiconductor
characteristics with their own conducting characteristics making regions of electron and hole abundances. Dopants are implanted into the crystal lattice of the silicon wafer by diffusion or ion implantation, both requiring sophisticated equipment for precision control of impurity doping quantities. The steps of thermal oxidation through impurity doping are repeatedly performed until structures like that of Figure 1 is achieved. The last step of fabricating a device on silicon is to deposit the metal interconnects, known as metallization, as well as the insulating layers between interconnects and chip components [13]. On completion of the last step of chip fabrication, the wafer containing many individual chips is coated with a protective layer and split up, typically by using a diamond saw to cut the chips apart. Once separated, the chips are packaged into standardized component packaging for sale.

Figure 1: An n-channel metal oxide semiconductor field effect transistor (NMOS) [15].

Though the silicon semiconductor fabrication process has been engineered for maximum throughput with smaller and smaller devices every year to satisfy Moore’s Law [16], not all applications require such small size, high precision, or quick computing speed. These applications may be solar energy, lighting, antennas, sensing, or smart packaging where durability, flexibility, cost, waste, and environmental demands are limiting factors, all of which
printing technology has the ability to satisfy [6] [17] [18] [19]. Printed electronics, in general, may be fabricated on flexible substrates with flex-compatible materials allowing for more durable, flexible, broad-application components. Conversely, affordable, low-waste rigid electronics may also be fabricated on rigid substrates using the same printing technology.

On top of meeting the demands listed above, printing electronics also reduces the large number of cleaning agents and hazardous materials used to fabricate silicon semiconductor devices. Comparatively, printed electronics have less environmental impact [3].

1.3. **Inkjet Printed Electronics Market**

The inkjet printed electronics market has emerged due to a multitude of driving factors, of which three of the greatest factors will be discussed. The first most likely major factor is the difficulty in advancing current silicon semiconductor technology. Moore’s Law, a prediction made by Gordon Moore in 1965, stated that the number of transistors on a silicon chip would double every year [20]. This statement held true until around 1975 at which the rate of transistors per chip began to slow causing Moore to revise his statement slightly – transistors per chip would double every two years [20]. Today, the transistors per chip doubles every 18 to 24 months, still holding true to Moore’s Law [16]. Moore’s Law is now becoming more difficult to satisfy, and researchers do not know if they will be ready to keep up with Moore’s Law’s steady pace [16]. Introducing printed electronics as a viable fabrication technique may take the stress off manufacturers’ struggle to further improve silicon chip technology and allow them to focus on alternative devices and materials, therefore, helping support research in printed electronics and create a new market.

Roll-to-roll (R2R) manufacturing is likely a second major driving factor causing growth of the printed electronics market. R2R manufacturing is a manufacturing and processing technique that utilizes substrates packaged as rolls and conveyor systems to decrease the time taken and real estate required to fabricate devices. Figure 2 illustrates the standard method of R2R
manufacturing including deposition, patterning, and packaging steps which may become a process of the past due to advancements in printing technology. Integrating an additive processing technique, such as inkjet printing, will form a mask-less, additive manufacturing process with the same advantages as that of a flat-bed printing process [21]. Along with R2R processing, mass-producing devices becomes more energy efficient which reduces device manufacturing’s environmental impact. Examples of devices that may be fabricated using R2R processing are photovoltaics, antennas, thin-film batteries, e-textiles, medical products, displays, sensors, and flexible memory [22]. Figure 3 shows examples of a few of these devices.

![Diagram of R2R manufacturing process]

Figure 2: Illustration of standard R2R manufacturing [23]

The third driving factor for increased market share of printed electronics is the overall growth of flexible and organic electronics. In 2010 the organic electronics roadmap estimated that the printed electronics market will exceed $300 billion over the next 20 years [24]. The printed electronics market in 2013 was predicted to grow from $3.4 billion to $13.2 billion in 2020 at a compound annual growth rate of 21.73% [22]. This past year, 2017, the projected market for flexible (flextronics) and organic electronics was predicted to grow from $29.28 billion in 2017 to $73.43 billion in 2027 with greatest market share in organic light emitting diodes (OLEDs) [25]. It is apparent that the market for organic electronic is growing and has the outlook
of continuing to grow. With nearly $29.28 billion in market share, the flextronics and organic electronics industry already consists of a respectable amount of the market. For perspective, Apple, the 9th largest US company, saw $217 billion in sales in the year 2017 [26]. The flextronics and organic electronics industry consisted of nearly 13% of Apple’s total sales even in its infancy.

Figure 3: Images of battery electrode (top left), organic LED (top right), and tandem solar cell (bottom) [22]

1.4. **Inks**

A multitude of functional inks are available as commercial products which is yet another factor for increased interest in printed electronic devices. Inks are of many types including organic, inorganic, and hybrid/nanocomposite materials [3]. These inks allow printing of patterns with electrical characteristics of conductors, insulators, and semiconductors, of which, the most
Conductive inks are critical building materials of properly operational devices, and there are numerous materials that may be selected to reach the best possible performance. These inks fall into the inorganic ink category which also has two sub-divisions: metal nanoparticle (NP) and Carbon nanotube (NT). The most common metal NP conductive ink is Silver (Ag) NP which has good conductivity of $6.5 \times 10^6$ S/m [1]. Other metal NP ink materials include Copper (Cu) and even Gold (Au). Cu NP ink is less often chosen over Ag NP due to undesirable oxidation after printing, however, Cu NP ink is lower cost, and post-process oxidation may be mitigated by protecting the Cu NP layer with an anti-oxidation shell of noble metals (Au, Ag, or Pt) [30] [31] [32]. Carbon NT inks have also been printed successfully in form of single-wall and multi-wall Carbon NT (SWCNTs and MWCNTs respectfully) [33]. SWCNT and MWCNT inks both hold advantageous properties such as excellent thermal conductivity, good mechanical strength, optical transparency, and semiconducting nature [3].

Organic materials simultaneously display the physical and chemical properties of organic polymers and broad range of electrical characteristics [34]. Inorganic materials, such as metal nanoparticles, have desirable characteristics, such as high conductivity and stability, but organic materials are more attractive in applications where low cost and mechanical flexibility are appealing. Organic materials for printing include those of insulating, semiconducting, and conducting electrical characteristics [35]. Chemical structure of the intrinsically conductive polymers may be modified to achieve desired electronic and mechanical, even photonic, properties [36]. Poly(3,4-ethylenedioxythiophene) (PEDOT) has been a great center of focus due to its high electrical conductivity of 400-600 S/m and its electrochemical stability, however, it is insoluble in common solvents, a major downfall when considering practical application in inkjet printing [34] [3]. To make PEDOT more appealing, the solubility was improved using poly-styrene-sulfonate (PSS) as a charge balancing counter ion doping polymerization. This is an
example of intrinsic organic polymer doping. Studies show that 3, 4-polyethylenedioxythiophene-polystyrene sulfonic acid (PEDOT:PSS) has exceptional capability of being an organic anode due to its 300 S/cm conductivity [37]. Research has been performed using PEDOT:PSS due to its optical transparency which is a characteristic desirable in the application of optoelectronic devices such as displays and LEDs.

Organic materials demonstrating characteristics of semiconductors are typically used to fabricate organic thin-film transistors (TFTs). These devices are designed for implementation in low-end applications because they are limited by low electron mobilities and slow switching speeds. Examples of these materials are regioregular poly(3-hexylthiophene) (P3HT), poly (triarylamine), poly(3,3-didodecyl quaterthiophene) (PQT), poly(2,5-bis(3-tetradecylthiophen-2-yl) and thieno[3,2-b] thiophene) (PBTTT), all of which are solution-based [37] [36].

In some instances, it is also desirable to print insulating materials. Thin layers of dielectric material may be printed to prevent leakage from one component to another or thick layers of dielectric material may be printed to increase the capacitance of a capacitor. Low-cost dielectric materials are available and may be dissolved in solvents to form printable solutions. Examples of these materials are poly (4-vinylphenol) (PVP), poly (methyl methacrylate), Polyethylene Terephthalate, Polyimide, Polyvinyl alcohol and Polystyrene [38] [29]. The printing of insulating materials is typically performed on a printed semiconductor/dielectric interface where material interaction is integral for satisfactory performance. Like OTFT layers, SAMs may also be used increase the performance of dielectric materials [39].

Each ink serves its own purpose and must be chosen carefully when selecting printing techniques or designing multi-layer devices. Surface tension, viscosity, density, and volatility are parameters that all affect the print performance of various printing machines. For example, the ideal fluid parameters for the DMP 2830 are 10-12 centipoise for viscosity, 28-42 dynes/cm for surface tension, higher than 100°C boiling point for volatility, and particle size 0.2 µm or less. Solvents and solutions used in inks have the potential of dissolving or reacting with previously
deposited layers, so compatibility of the solvents with the underlying materials is critical [39]. For example, an OTFT is a multilayer device with metal contacts and organic layers printed in successive layers.

The two inks studied in this thesis are both Ag NP inks due to their ability to print on glass and coated substrates. The first ink is Novacentrix JS-B25HV which is designed for Novacentrix Novele and Photopaper substrates. JS-B25HV ink has 25 wt% of Ag NPs and thin film sheet resistance of 50 mΩ/sq, approximately 1.8x bulk Ag resistivity. The second ink is Novacentrix JS-B40G which is designed for glass, uncoated plastics, and ceramics. JS-B40G ink has 40 wt% of Ag NPs and thin film sheet resistance of <1.7x bulk Ag resistivity. This ink must be cured at or above 180°C.

1.5. Substrates

The availability of a many purposeful substrates greatly increases the scope of printed electronics’ applications. There are two types of substrates typically used for print processing: flexible and rigid. Flexible substrates comprise of most printed substrates because they can withstand a large amount of bending, stretching, and thermal cycling without significant damage. The most prevalent flexible substrates are polyethylene terephthalate (PET), polyethylene naphthalate (PEN), and polyimide (PI) films. It is critical to match the substrate characteristics to withstand the demands of ink processing. For example, Novacentrix JS-B25HV ink requires thermal sintering near 220°C to become a sheet of printed conductive metal, but substrates such as PET and PEN cannot withstand temperatures above 70°C and 120°C respectfully. Special inks have been designed for compatibility with low-T substrates, likewise, high-T substrates have been designed for high-T processing inks Figure 4 displays the glass transition temperatures of some common polymer substrates. Though thermal sintering is a limiting process, other methods of sintering are available such as phontonic, electrical, and microwave sintering [40] [41] [42] [43]. These methods of sintering are largely designed for metal NP inks
due to the demand for relatively higher temperatures. Energy is delivered from optical, electrical, or microwave sources to the printed patterns to rapidly heat and sinter the nanoparticles without harming the underlying materials or substrate.

![Temperature Ranges of Polymer Substrates](image)

**Figure 4:** Glass transition temperature of common polymer substrates [19]

Other flexible substrates include papers, which may be used in smart packaging and microfluidic applications at even lower cost than polymer substrates. Research has been performed by printing devices, such as antennas, on photopapers that have desirable print characteristics [8]. Another appealing type of flexible substrate is flexible/stretchable which may be used in biomedical or other conformal sensor applications. An example of this type substrate is the Dragon Skin, a Silicone-based material, that has been used to mount sensors conformally on skin as well as robotic joints [44]. Though most substrates chosen for inkjet printing are flex-type substrates, rigid and semi-rigid substrates have application in areas where the flex-demand is not of concern. These areas include microfluidics, sensors, and radio frequency (RF) devices.
Common substrates include those of plastics, glass, silicon, ceramics, and rigid metal sheets [45].

1.5.1. Role of the Substrate

The substrate is a vital component of printed electronic devices, and it serves a multitude of purposes ranging from structural support to improving electrical performance. On top of providing advantageous characteristics, the substrate may inhibit the performance of devices in areas including magnetic properties and ink-substrate adherence. In this section, numerous effects and characteristics of the substrate are introduced and discussed.

The first, likely most obvious, characteristic of the substrate that influences printed electronic quality is the interaction between ink and substrate. This characteristic may be broken into two components: ink adherence to substrate and substrate acceptance of ink. The adherence of ink onto the substrate is heavily dependent on the mechanical properties established once the ink has been sintered on the substrate [1]. Strong mechanical interaction will provide quality printed traces; for example, the Ag NP traces printed in this thesis were resilient to the bending and deformation of the substrate because of the strong mechanical ink-substrate interaction. The acceptance of the ink onto the substrate is heavily dependent on the contact angle of the ink droplet on the substrate. This characteristic is most noticeable on substrates with very small droplet contact angles where leeching and pattern boundary stability is weak [1]. To improve these metrics, operations, such as plasmonic surface activation, are available. Though surface optimization can improve ink-substrate interaction, there are external effects separate from the substrate, such as ink solvent evaporation, that may help or inhibit print quality.

Another characteristic to discuss is the effect of the substrate on the electrical and magnetic characteristics of the printed device. Materials, such as the polymers used in this thesis, hold measurable properties that may be implemented into the designs of capacitors,
inductors, antennas, as well as semiconductor devices. These measurable properties are the relative permeability ($\mu_r$) and relative permittivity ($\varepsilon_r$) which have a particularly direct effect on the inductance and capacitance respectively. The overall permeability and permittivity are both functions of the vacuum permeability and vacuum permittivity as shown in the equations $\mu = \mu_o \mu_r$ and $\varepsilon = \varepsilon_o \varepsilon_r$ where $\mu_o = 8.85 \times 10^{-12} \, \text{F/m}$ and $\varepsilon_o = 1.256 \times 10^{-6} \, \text{H/m}$. For example, the equation for capacitance is $C = \frac{\varepsilon_r \varepsilon_o A}{d} = \frac{\varepsilon A}{d}$ which shows that increasing $\varepsilon_r$ causes an increase in capacitance. Though the capacitors in this thesis were printed on the surface of the substrate, there was a portion of the field contained within the substrate which ultimately influences the capacitance. In RF applications, the permittivity and permeability have complex components which are dependent on frequency. This characteristic is valuable, but it is not within the scope of this thesis and is not discussed in any detail.

The final substrate characteristic to mention is the amount of “backbone” that a substrate offers. Some inks may be brittle, fragile, or inflexible which requires a rigid substrate such as glass or ceramic. Another application for the rigid substrate is the antenna because geometric distortion away from the original antenna design may cause the radiation characteristics to become sub-optimal. Other inks are flexible which allows them to be printed on flexible substrates, such as plastics or papers. More extreme devices are flexible and stretchable requiring hardly any backbone at all. An example substrate that would serve in extreme conformal applications is the Dragon Skin [44] which was mentioned previously. The backbone of a substrate also has great effect on the characterization of some devices. For example, the bending sensor that is described in this thesis depends heavily on the bending properties of the device. Technically speaking, the substrate is the vessel on which the bending is performed, and the ink is the measurement medium that measures the magnitude of the bend.
1.5.2. **Substrates in This Thesis**

This thesis encompasses three substrates: glass, Novacentrix Novele IJ-220, and Epson Photopaper. This section introduces the substrates in greater detail and points out some important characteristics as described above. Note that for the rest of this thesis, Novacentrix Novele will be referred to as Novele PET, and Epson Photopaper will be referred to as photopaper.

The glass substrate used in this thesis was a large 50 mm x 75 mm glass microscope slide. The slides came packaged in a cardboard box with wrapping plastic, but the slides still required cleaning for performance improvement. Further cleaning results are discussed in a later section. Characteristics important to the application of this thesis were the relative permittivity, equal to approximately 3.7, and the supportive rigidity. JS-B25HV was an inflexible ink that was printed on glass. Due to glass’s advantageous rigidity, print quality with this ink was improved.

Novele PET was another useful substrate within this thesis. This substrate was a pre-activated, nano-porous substrate which was pre-packaged in a plastic film. No cleaning was necessary before printing on Novele PET which was ideal because it made for a consistent print-quality substrate. The characteristics that were valuable within the work of this thesis were the relative permittivity, equal to approximately 2.6, and the flexibility. This substrate was the choice substrate for both the bend sensor as well as the wax microfluidic sensor. The main advantages this substrate brought forth were the excellent print quality due to the pre-activated surface and the mild hand-bendability.

Photopaper was the final substrate of choice for printing within this thesis. Photopaper was a nano-porous PET-coated paper which also offered excellent printing characteristics. Performance metrics of the photopaper were like those of the Novele PET. Like Novele PET, the valuable characteristics of photopaper were the relative permittivity, equal to approximately 3, and the flexibility. This substrate was the choice substrate for fabrication of the square planar
inductors due to its excellent printing characteristics. The sheet resistivity was able to be greatly reduced, therefore, producing relatively large phase angles.

It is crucial to commit some effort to understanding the effects of the substrate, especially in precision applications such as sensing, antennas, and active circuit components. These three substrates are further reviewed in a later chapter where sheet resistivity, drop sizes, and other metrics were measured and discussed.

1.6. Thesis Goal

The goal of this thesis is to optimize the Fujifilm DMP-2830, a useful new machine to the electronics fabrication labs at Ohio University whose purpose will be to print electronic devices such as sensors, transistors, antennas, and solar cells. This thesis will also present detailed characterization of two Ag NP inks, Novacentrix Metalon JS-B40G and JS-B25HV, and the effect of changing printing and processing parameters, such as drop spacing and number of layers, on the sheet resistivity. Three substrates are used to study sheet resistance of these inks: glass, Novele PET, and photopaper. This thesis will also present the characterization of printed resistors, capacitors, and inductors as well as the effect of changing parameters, such as line width and number of turns, on the components’ values. The tests, processes, and discussions for the characterization of inks, substrates, and electronic devices will also be useful for introducing new fabrication materials to the electronics fabrication labs as well as serve as a training tool for students and researchers new to the Fujifilm DMP-2830 printing system. Finally, practical application of two sensing devices fabricated with the DMP-2830 are discussed. One sensor is a resistive bend sensor on flexible platform and the other is a capacitive microfluidic wax channel sensor also based on a flexible platform. The practical applications of the DMP-2830 printing system is not limited to these two devices, instead, they are quite broad, making the primary objective of this thesis to establish a large-scale process that may be widely used to fabricate a multitude of devices.
CHAPTER 2: BACKGROUND

2.1. Inkjet Printing History

The history of inkjet printing is quite brief with its origins dating back to the nineteenth century beginning with the work of many brilliant minds researching fluid dynamics. Just as most advanced technologies begin, inkjet printing materials began with establishment of the fundamentals through the works of Thomas Young, Pierre-Simon marquis de Laplace, and Felix Savart. Young, in 1805, established the existence of a relationship describing the contact angle between fluid and solid materials [46]. The discovery of such relationship provided assurance that the interaction of an ink on a substrate is not at all random. An illustration of Young’s contact angle discovery is shown in Figure 5.

![Contact Angle Illustration](image)

Figure 5: Illustration of the contact angle of a droplet on the surface of a solid [47]

2.1.1. Origin of Jetting Fluids

The jetting of fluids was first approached by Savart in 1833 who showed that the breakup of liquid jets into repeatable drops is governed by the laws of fluid dynamics [48]. On top of the research performed by Young, Laplace, and Savart, research focused solely on ink jetting was performed. In 1856, Plateau published an article describing the formation of jets from
circular nozzles. In 1931, Weber explained the formation of droplets from the breakup of viscous liquid jets [48].

2.1.2. First Inkjet Printing Devices

These works eventually compiled to become the creation of the first inkjet printing devices available on the market. One of the first commercially available inkjet devices was designed by Rune Elmqvist of Siemens-Elma which was integrated into the mingograph, one of the first commercially available inkjet data recorders of analog voltage signals for medical applications [48]. Another first-generation machine was built by Stanford University professor Dr. Sweet who produced one of the first Continuous Inkjet (CIJ) printers in 1965. The CIJ printer jetted ink by applying force to a liquid jet to induce the breakup of the liquid stream into a series of droplets with uniform size and spacing. The droplets were able to be steered onto the substrate by charging the drops and passing them through an electric field. Ink droplets not charged were sent into a recycling gutter [49]. IBM later commercialized this technology to produce the IBM 4640 printer in 1976. For the application of printing functional materials, the complexity of the CIJ printing system is not supportive due to ink exposure to atmosphere during the recycling process of uncharged ink droplets [48].

In the late 1940s, the Radio Corporation of America produced one of the first drop-on-demand (DOD) systems, the successor of the CIJ inkjet system. The design of this printer was intended for use in the fax machine. The jetting process of this printer was triggered through transient pressure waves produced by a voltage driver that mechanically deformed a piezoelectric disc. This device had potential to for market introduction but never went into production [50]. Another inkjet driving technique, thermal inkjet printing, was designed and patented by Mark Naiman of the Sperry Rand Corporation. Naiman’s print head operated by resistive superheating of the ink within the ink reservoir to thermally expand a bubble leading to fluid displacement of the ink, therefore, jetting the ink out of the nozzle. The voltage to the
heating element was relieved causing a transient pressure wave within the nozzle to separate the droplet from the ink in the nozzle [51]. Thermal inkjet printers have been sold by Hewlett Packard and Canon under the Thinkjet and Bubblejet brands. Due to the thermal operation of these print heads, they are not optimized for printing of functional materials [48]. Figure 6 illustrates a thermal inkjet print head.

Figure 6: A thermal inkjet print head schematic (left) and squeeze-mode print head schematic (right) [48]

In 1972, the patent was awarded to Zoltan of the Clevite company for a DOD system composed of hollow-tube piezoelectric elements. The print head in this design was known as the squeeze-mode print head because it utilizes contracting piezoelectric electrodes to squeeze the ink chamber and force droplets out of the nozzle [52]. Figure 6 illustrates the squeeze-mode print head. Like the squeeze-mode print heads, bend-mode print heads utilize the functionality of a bendable ink chamber. The DOD print head described by Stemme of Chalmers University in 1972 jetted ink by utilizing an electrically excited piezoelectric disk to flex its ink chamber inward. The inward motion of the chamber wall reduced the volume of the chamber and forced ink droplets out of the nozzle. The piezoelectric jetting frequency of this device was
approximately 700 Hz [53]. An illustration of this print head is shown in Figure 7. Bend-mode print heads have been sold by Tektronix, Xerox, Kyocera, and Epson [48].

Another membrane-based print head was the push-mode print head that was patented in 1984 by Howkins of the Exxon Company. This print head was also known as the bump-mode print head and had a piezoelectric rod placed next to a membrane that acted as a plunger on the membrane. Electrical excitation of the element caused it to expand and push the rod against the ink chamber wall and, therefore, jetting a droplet [54]. An illustration of the bump-mode print head is shown in Figure 7.

The final type of piezoelectric DOD print head is the shear-mode print head which was patented by Fischbeck and Wright of the Xerox Corporation [48]. The shear-mode print head was designed such that shear deformation of the piezoelectric element was used to deform the upper half of the ink channels. The deformation was mirrored in the lower half of the ink channels which forced the channels into a chevron shape to induce droplet ejection [55]. An illustration of the shear-mode print head is shown in Figure 7.
2.2. Various Printing Technologies

Traditional fabrication techniques, such as photolithography, require a great amount of energy, space, power, and funding which is why interest in new additive fabrication techniques are being explored [1] [30] [6] [56]. Much of this interest is being directed toward the printing of functional materials with technologies that include, but are not limited to, inkjet printing, screen printing, capillary action printing, and aerosol jet printing [57]. Each of these printing techniques serve their own purposes in the additive fabrication process and have advantages and disadvantages that allow each technique to carry the weight of specific processes such as large area printing or fine pattern printing [56].
2.2.1. **Inkjet Printing**

Inkjet printing of functional materials demands a considerable amount of the inkjet printing machine, especially the print head, because of the limitations of the inks. Inkjet printing machines such as the CIJ and thermal inkjet print heads were unqualified to jet functional materials due to their operation. The CIJ recycled material by directing it to an open gutter making the machine less wasteful, but this exposed the unused material to the external atmosphere leading to potential contamination, evaporation of solvent, and settling of particles [58]. The superheating cycle of the thermal inkjet print head was undesirable due to functional material sensitivity to heat [59]. For example, many commercially available inks are thermally sintered at temperatures at or above 100°C which is much lower than the temperature of a superheated fluid, and molecular structure of some functional materials may be altered with the high energy produced by the superheating process. The demand for specialized machines has led to a wide variety of inkjet printing devices that have extremely mobile settings to meet the demands of functional inks while also broadening the ability to print on a multitude of purposeful substrates.

Traditional fabrication techniques require extremely large plants with precision equipment and many hazardous chemicals. Typically, devices manufactured in this setting are so costly that very large orders of product must be placed to reach the break-even-point [60]. Inkjet printing fabrication processes avoids many of the drawbacks of traditional device fabrication by simplifying the fabrication process.

First and foremost, the inkjet printing fabrication process is simpler than the traditional device fabrication process. Inkjet printing is strictly an additive process, meaning that materials are printed onto a substrate layer by layer without the use of lithography techniques or masking for pattern formation. Inkjet printing machines create a direct path from drawings and patterns created in computer aided design software into layers of or complete working devices [60].
Cleaning processes are significantly less complicated than those used in traditional fabrication techniques because strong acids and other hazardous solvents present in these techniques are replaced by methanol, ethanol, and de-ionized water. Most substrates, such as papers and plastics, are cleanly packaged from the manufacturer and do not require pre-fabrication cleaning processes. An example of such a material is the Novacentrix Novel, a polyethylene terephthalate (PET) substrate cleanly packaged with one side having a manufacturer surface activation.

The materials and fabrication processes involved with inkjet printing machines also provides for lower cost, throw-away, and recyclable products. Simple substrates, such as plastics, textiles, and papers, are all commercially available and affordable compared to silicon substrates that require meticulous preparation and complicated doping processes with rather rare and expensive elements.

Two types of inkjet printing machines will be examined in this section: inkjet printing machines for research and inkjet printing machines for commercial fabrication, both Fujifilm Dimatix machines. These machines, and others like them, demonstrate the superiorities to traditional fabrication techniques mentioned in the previous section. The cornerstone of Fujifilm Dimatix’s printing products is the shear-mode jet actuator [61]. Figure 8 illustrates the fundamental operation of the shear-mode print head used in the Dimatix printing systems.

![Image of shear-mode print head]

Figure 8: The Dimatix shear-mode print head in relaxed state (left-most) and with electric field applied to the piezoelectric (right-most) [61]
2.2.1.1. Fujifilm DMP-2831 for Research

The inkjet printing machine of choice for the research in this report was the Fujifilm Dimatix Materials Printer DMP-2831 (DMP), a laboratory benchtop digital inkjet printing system designed for rapid prototyping. The DMP is a highly versatile machine capable of jetting a wide range of fluids with quick interchangeability of print heads capable of 5 µm drop spacing [62]. There are 2 print heads available for this system, one printing 1 pL and the other printing 10 pL per drop. The viscosity of these print heads is limited between 10 and 12 cP at operating temperature, but the print head is capable of withstanding nanomaterials and strong chemicals. The DMP-2831 can print patterns up to 200 x 300 mm on its thermally controllable, vacuum print platen capable of holding substrates up to 25 mm in thickness. Bench top inkjet printing devices for lab purposes and research are not optimized for high throughput operations, thus producing large numbers of test devices would be costly in time. Instead, benchtop systems typically represent the operation and functionality of their larger manufacturing counterparts enabling researchers to rapidly design, print, and test prototype devices. Figure 9 shows an image of the Fujifilm DMP 2831 print head under a stereoscope. The DMP-2831 utilizes two cameras to perform cartridge and substrate calibrations as well as substrate examination and measurement along with enabling the user to individually calibrate each cartridge nozzle. Later in this thesis, optimization of the calibration and printing process using the DMP is explained.
Figure 9: Bottom of the Fujifilm DMP 2831 print head as seen through a stereoscope. Note that the 16 nozzles are 254 µm apart

2.2.1.2. Fujifilm DMP-3000 for Manufacturing

The DMP-3000 is the larger counterpart of the DMP-2800 model printer wielding a 128 nozzle print head with a 508 µm spacing between nozzles. There are two print heads available, the SE3 and SX3 print heads, offering 35 and 8 pL volumes per drop respectively [63]. The DMP-3000 also has a temperature controllable vacuum platen but is 300 x 300 mm in size – slightly larger than the platen of the DMP-2800 series printers. The operation of the DMP-3000 printing system is highly representative of the smaller DMP-2800 series printers containing the two calibration and measurement camera systems as well as the individual nozzle calibration feature [64].

2.2.2. Screen Printing

Screen printing has been established as one of the simplest and most cost-effective printing techniques and has been used by electronics manufacturers to fabricate large-area
prints. The technique is based on a specially woven screen with different thread densities and thicknesses to obtain a desired pattern. To print a pattern, the substrate is placed flat with the screen on top. The screen is covered with the desired ink and a squeegee is driven across the screen forcing the screen to contact the substrate surface. This causes the ink to be ejected through the exposed areas of the screen onto the substrate, thus printing the desired pattern [65]. This type of screen printing is known as flat-bed screen printing. Figure 10 shows an illustration of a simple screen printing process.

![Figure 10: Flat-bed screen printing process illustrating the “movement” of the squeegee [66]](image)

There are two other screen printing techniques: cylinder and rotary. Cylinder screen printing is like flat-bed printing except the substrate is attached to the screen roll. The screen roll is pressed and rolled on a surface which forces the screen to contact the substrate to deposit the ink. Rotary screen printing is much different than flat-bed and cylinder screen printing in that it utilizes the simultaneous rotation of substrate and screen for “movement” of the ink squeegee. The squeegee action is the same as flat-bed printing but instead the squeegee is placed within the screen roll. Rotary screen printing is the preferred screen printing technique for manufacturing because it allows for roll-to-roll manufacturing and much higher throughput [67]. Figure 11 illustrates the rotary screen printing process. Screen printing is a good alternative to
subtractive lithography processes because of the lack of chemical etching making an environmentally-friendly, low-cost alternative. Inks can be screen printed and sintered using optical, microwave, thermal, or electrical sintering techniques. Though screen printing has been proven to work well in roll-to-roll environments, the resolution is not comparable to the subtractive fabrication techniques. Another challenge facing screen printing is that layer consistency is difficult to achieve [66]. Screen printing may be used in conjunction with inkjet printing machines to satisfy the low resolution, large area patterns of antennas, solar cells, or LEDs while the inkjet printing machine satisfies the higher resolution, smaller patterns required in the design of these devices.

Figure 11: Illustration of a rotary screen and rotary screen process [68]

2.2.3. Capillary Action Printing

Sonoplot® offers a small lineup of products capable of performing capillary contact microplotting for a wide range up applications including deposition of functional materials. Capillary contact microplotting utilizes the cohesive property of the ink along with a Lead
Zirconate Titanate piezoelectric driver plate to continuously deposit ink on the substrate surface. The piezoelectric driver resonates at ultra-sonic frequencies to push picolitre volumes ink out of a user-fabricated glass tip to achieve ink traces down to 5 µm in size. Manufactured tips are capable of printing even smaller features but come at a higher cost. Unlike other printing machines restricted to low-viscosities of 5 to 20 cP, the microplotter is capable of jetting fluids up to 450 cP [69]. The utilization of this printer in conjunction with inkjet printing machines may allow for deposition of significantly higher viscosity fluids while simultaneously satisfying smallest dimensions requirements of printed organic thin film transistors (OTFTs) and capacitors. An SEM image of a gold coated glass microcapillary nozzle is shown in Figure 12.

![SEM image of microcapillary nozzle](image)

Figure 12: SEM image of microcapillary nozzle [3]

### 2.2.4. Aerosol Jet Printing

Aerosol-jet printing (AJP) is a 3D inkjet printing technique capable depositing functional materials on flat surfaces as well as 3D surfaces. Optomec offers a line of AJP machines with various options and features including, but not limited to, multiple axes (up to 5), feature sizes,
sintering tools, 2D or 3D fabrication capability, and work area sizes. The Optomec line of printers utilizes jets of air to propel atomized ink from a pneumatic atomizer through an annular nozzle onto a substrate surface. Droplets larger than 5 µm are cycled back to the ink reservoir and droplets of <5 µm are propelled through the nozzle. The particle stream is removed of excess gas before exiting the nozzle to produce features 10 µm and less [70]. An illustration of the AJP printer operation is shown in Figure 13. Unlike inkjet printing, screen printing, and microplotting, the AJP systems can print, in low volume, on surfaces that require conformal type printing, such as domes, cones, and curvatures. AJP systems may be used to print on surfaces that inkjet printing systems cannot print on, and, henceforth, may be used with inkjet systems to print the low-volume components of complete printed systems.

Figure 13: AJP printer operation [68]

2.3. Printed and Flexible Applications

The flexible nature of nearly every substrate designed for printing greatly increases the breadth of application for printed electronics, and the availability of printable and modifiable inks adds even more device application. Devices under study, and even production, include wearables, displays, energy storage devices, circuit elements, medical and healthcare devices, sensors, memory devices, photovoltaics, and antennas. A few of these devices are further
investigated in this section to illustrate the potential of printed electronics in general and the printing process that was developed in this thesis.

2.3.1. Wearables

The number of wearable devices has greatly increased since the coming of flexible electronic technology. Included in this genre of devices are e-textile and skin-mounted electronics. E-textiles, also known as smart textiles, extend the usefulness of standard fabrics and may be divided into three sub-types: passive smart textiles that are able to sense the environment or user based on sensors, active smart textiles that integrate an actuator function and sensor that respond to stimuli from the environment, and very smart textiles that are able to sense, react, and adapt their behavior [71]. Materials used range from NP inks, metal-woven fabrics, and functional polymers to electrochemical materials used for sensing. E-textile devices have practical application in the biomedical industry and have been demonstrated as electrocardiogram (ECG) [72] and electromyography (EMG) [73] sensing devices. E-textiles also have been fabricated that measure other metrics such as oxygen, salinity, and contamination [74] [75]. On top of sensing, power generation and storage devices also have application in e-textiles to create self-powered wireless sensing systems. Power generation through piezoelectric elements [76] and photovoltaics [77] have been demonstrated on e-textiles. A study was conducted utilizing polymer-based organic compounds coated on polypropylene fibers; the study achieved a maximum short-circuit current density of 0.27 mA/cm² [78].

Skin-mounted electronics have a wide range of applications especially in sensing various body chemistries and body motion. Sensors that monitor body chemistries may exist as tattoos [79], skin-printed [80], and electronic skin (e-skin) [81]. These same device topologies may also be designed to monitor body motion. Skin-mounted sensors also have very broad application in the biomedical industry, and many devices have been explored that exploit the
flexible, durable, body-compatible nature of skin-mounted electronics. An example of this type of device is a carbon NT-based capacitive strain sensor with fast response and high optical transparency characteristics which is mounted on a glove. The sensor demonstrated high durability and measurement of strains as low as 1% and as large as 300% [82]. Fully integrated, wireless sensor suites have also been designed that are able to measure full-body motion metrics for detection of movement patterns from neuromotor disorders, such as Parkinson’s Disease, epilepsy, and stroke [83].

2.3.2. Displays and LEDs

The LED is essentially a p-n junction diode typically made from direct bandgap semiconductor materials, such as GaAs, in which electron-hole pair recombination results in the emission of a photon approximately equal to the bandgap energy [84]. Within the direct bandgap semiconductor material, p-type (acceptor) and n-type (donor) regions are doped to form a region at which electron-hole recombination occurs; this is called the active region [84]. Doping of these regions requires similar techniques and equipment as those required in conventional semiconductor fabrication. Organic polymers have been engineered to perform as donor and acceptor materials with bandgap energies desirable for emission of light in the visible spectrum.

Displays and light LEDs that utilize organic semiconductor materials have been around for quite some time and have been growing steadily at a rapid rate, but, recently, flexible platforms are receiving an extraordinary amount of attention. Entire displays are made of individually addressable components called pixels. On modern devices, these pixels are clusters of individually addressed LEDs of RGB color. LED pixels have allowed displays to become extremely thin because LEDs produce enough light to operate without the need for an auxiliary light source. Silicon integrated circuits have been following a trend of reducing the size of devices and packing more devices in smaller amount of area. Displays have not followed this
trend; in fact, number of devices in an area has been consistent where the substrates have greatly increased in size [85]. Since substrates are becoming larger, the need for larger masks and lithography tools increases. R2R manufacturing is an enabling process for flexible displays because they may be fabricated using printing techniques, therefore, removing the necessity for large masking and complicated lithography techniques. In 2005, Zyung et al. [17] demonstrated the emission of white light from stacked RGB structure utilizing flexible organic LED (OLED) electrochemistry. The white OLED (WOLED) luminance varied from 400-4000 cd/m² as the applied current densities changed from 10-100 mA/cm². The luminous efficacy of the fabricated WOLED was 1.8 lm/W. Fast forwarding to 2017, a WOLED with luminous efficacy exceeding 100 lm/W, an over 5000% increase from the WOLED in 2005, was fabricated [86]. The luminous efficacies of today’s highest performing LEDs are around 160-170 lm/W [87], and OLEDs are converging on higher efficiencies leading to competition between non-organic and OLED light sources which is indicative of the market prediction stating that most of the printed electronics market will be in that of displays. Figure 14 illustrates the forecast of OLED applications from year 2000 to 2020. Figure 15 illustrates the enabling OLED technology for specific product applications.
Figure 14: Forecast of OLED applications [88]

Figure 15: Correlation of OLED technology and product application [120]
2.3.3. **Energy Production and Energy Storage Devices**

Flexible and printable energy and energy storage devices include fuel cells, super-capacitors, and thin-film batteries. Fuel cells are electrochemical devices that convert hydrogen or hydrocarbon fuels (such as butane and propane) into electrical power without the need for combustion. These power-generating devices interest researchers because they are clean-running typically using H₂ and O₂ molecules as fuel to produce only water, electricity, and heat. Carbon emissions may become the past. Fuel cells have similar characteristics to that of a battery: they are stackable and are electrochemical devices with many membranes and layers. A single fuel cell may generate a small amount of power, but multiple cells may produce enough power for larger power applications from use in mobile devices to use in electric vehicles.

Flexible fuel cells based on a proton exchange membrane (PEM) have been studied. The designs are based on a plenum (a space capable of holding a reactant) enclosed by flexible walls with flexible anodes and cathodes on opposing walls making the cells stackable [89]. A 1x1 cm², air breathing, PEM fuel cell (PEMFC) demonstrated by [90] exhibited specific volume power density nearing 5190 W/L with outstanding bending performance, capable of being bent 600 times and more while retaining 89.1% of its original performance. A demonstration of the fuel cell in operation is shown in Figure 16.
Another energy storage device with rather high interest is the super capacitor, also known as a supercap. Super capacitors are, essentially, capacitors that have an extremely high capacitance capable of storing significantly more energy and discharging more current than standard capacitors. The super capacitor has also been described as the branch between standard capacitor and battery because of its quick discharge and high energy storage characteristic. Flexible super capacitors have application in flexible electronic devices because, simply, all devices need power, and some require more power over shorter time. Materials such as graphene, carbon nanotubes [91], and electrolyte-saturated paper substrates [92] are a few enabling materials for flexible super capacitors. Flexible super capacitors have been demonstrated that exhibit a maximum power density of 390.53 kW/kg and extreme mechanical durability with a 95.9% retained capacitance after 5000 cycles [93].

Unlike the supercapacitor, there is larger application for the flexible battery in flexible electronic devices because they are a more stable, sustained power source. Flexible batteries are also an electrochemical device with the reaction product being electricity. Traditional, non-
flexible batteries have a generic structure illustrated in Figure 17 which is the structure maintained by the flexible battery.

![Lithium-ion battery structure](image)

Figure 17: Lithium-ion battery structure [94]

The flexible battery has been fabricated using various techniques, including printing techniques, using a wide range of materials including metal oxides [94] [95], carbon nanomaterials [96], and even papers [97]. A promising battery chemistry for flexible electronic devices is lithium-ion technology which has been demonstrated in many recent studies. In a study by [98], a non-printed, flexible lithium-ion battery was fabricated based on Li$_4$Ti$_5$O$_{12}$/graphene (LTO/GF) and LiFePO$_4$/graphene (LPF/GF) foam electrodes and ethylene carbonate/dimethyl carbonate electrolyte. The battery’s performance was measured at a 10-C charge/discharge rate, and the battery’s capacity was 117 mAh/g. Comparatively, the 10-C capacity is approximately 88% of the 1-C rate which surpasses the capability of most full battery designs [98]. The battery was also able to be cycled at the high rate of 10-C over 100 times with only 4% capacity loss.
2.3.4. Sensors

Sensing devices have an extremely broad scope of application because they are used in the medical industry, avionics, controls, the food industry, and even smart-home technology. Examples of sensors that have been designed on flexible platforms include devices that sense body metrics [99] [79] [80], gas content [8], humidity [100] [101], water quality [102], touch [4], temperature [103], and light [104]. The devices that accomplish the actual sensing are capacitors, inductors, RF devices, as well as phototransistor devices for photodetectors.

Materials used to fabricate these devices are metal nanoparticles, chemical analytes, quantum dots, organic compounds, and polymer substrates. Sensors may also be electrochemical devices with analytes that react to desired chemicals and physical-type devices that measure metrics such as permittivity, temperature, and humidity.

Perhaps the simplest type of sensor is the capacitive-type sensor because capacitors are simple structures may be inkjet printed on flexible substrates, such as paper or plastic. Capacitance \( C \) is a metric that is a function of electrical permittivity \( \varepsilon \), distance between parallel plates \( d \), and cross-sectional area \( A \) of the capacitor and is represented by the equation \( C = \frac{\varepsilon A}{d} \). Inkjet printing devices have been used to print capacitors, and, though the printed capacitors are 3-D (length, width, and height of trace), the height of the printed trace is insignificant compared to the length and width making the structure a simple 2-D structure. An example of a 2-D printed interdigital capacitive touch sensor is shown in Figure 18. This sensor is a series LC-resonant circuit and touch sensor in one package. Resonance of the circuit is a function of frequency \( f \), capacitance, and inductance \( L \) and is represented by the equation \( f_{\text{resonant}} = \frac{1}{2\pi \sqrt{LC}} \). The capacitor acts as the sensor and the inductor acts as the power coupling device for a wireless-type sensor reader. At rest, the capacitor’s permittivity is mainly that of air (substrate permittivity also influences total permittivity), and the capacitance changes when a
finger is placed on the capacitor making the permittivity of flesh the new permittivity of the capacitor, thus changing the resonance of the circuit [4].

![Figure 18: Design of a contactless LC-resonant touch sensor [4]](image)

Another type of sensing technique that exploits the convenience of capacitive components is in microfluidics. Microfluidics are especially appealing in the biomedical industry due to the requirement of an extremely small amount of fluid to perform measurement functions, but microfluidics are not limited to biomedical sensing devices. Fluids have been passed over capacitive devices using microfluidic channels fabricated in polydimethylsiloxane (PDMS) [105] and also by fabricating hydrophobic surfaces to contain fluids in small channels [106] [107]. Studies have been performed that utilize wax, as hydrophobic material, printed on paper to contain fluids in microfluidic channels [108] [109]. The wax channels act as a barrier to contain fluid in small paper regions where analytes or capacitive sensing components are present for chemical sensing. Other applications utilize the channel to measure flow rate and even viscosity [106].
2.3.5. **Photovoltaics**

Photovoltaic devices, better known as solar cells, are devices that convert the incident radiation of the sun into electrical energy. Solar cells operate because of the photoelectric effect: when light energy enters a material and is absorbed, charged particles called electrons ejected [110] from the material and can be used as electric potential. Conventional solar cells are built upon Schottky junctions, p-n junctions, or p-i-n junctions in which the acceptor and donor regions [84] are fabricated using similar doping techniques as conventional semiconductor doping. Conventional solar cells are not flexible and have rather power consuming and complex manufacturing processes that may be avoided using other materials that operate on the photoelectric effect with flexibility and printability.

Organic materials have application in the solar cell due to their mechanical flexibility, printability, and low-cost [111]. They operate under the same basis as the conventional solar cell with donor and acceptor regions, but, rather than ion implantation for doping, the organic semiconductor is designed as an intrinsic donor or acceptor material. Another benefit is that organic solar cells have been fabricated without indium tin oxide (ITO), the common cathode material which is transparent, inflexible, and conductive [112]. Indium is scarce, therefore, leading to a costly electrode material. In a recent study [112], the ITO cathode was replaced with a thin film metal electrode made of Ag which promoted mechanical flexibility. The majority of layers involved with the function of this solar cell were thermally evaporated, but the organic poly (3-hexylthiophene):[6,6]-phenyl-C61 -butyric acid methyl ester (P3HT:PCBM) active layer was spin coated, a process that may be replaced by printing. The composed solar cell is shown in Figure 19 on a PET substrate. This study produced a flexible organic solar cell with 2.50% power conversion efficiency (PCE) compared to the same device on a rigid glass substrate with PCE of 2.71%. There is rather small difference in efficiency when comparing the glass solar cell to the PET solar cell.
Though organic solar cells are a viable alternative to the conventional solar cell, there is a need to improve the power conversion efficiency in order to compete with alternative energy sources. To do this, organic solar cells are required to have estimated 5-10% power conversion efficiency with a lifetime of 5-10 years [113].

![Layers of the flexible organic solar cell on PET substrate](image)

Figure 19: Layers of the flexible organic solar cell on PET substrate [109]

Another solar cell that has been receiving much attention lately is the perovskite solar cell, and it may be printed on flexible substrates. The perovskite material used in perovskite solar cells reflects the same structure \((ABX_3)\) as the actual perovskite, a mineral composed of calcium, titanium, and oxygen \((\text{CaTiO}_3)\), which is where the name “perovskite” comes from. The most efficient devices have been produced with the following materials: A=methylammonium \((\text{CH}_3\text{NH}_3)\), B=lead(II) \((\text{Pb}_2^+)\), and X\(_3\)=chloride \((\text{Cl}^-)\) or iodide \((\text{I}^-)\) [114] [115]. Figure 20 shows the advancement of solar cell technology with devices based on Si, cadmium tulluride \((\text{CdTe})\), organics, and perovskites. It is observable that perovskite solar cells have extremely high potential in solar cell applications with nearly the same efficiency as the most efficient solar cells. Research has been performed on printed perovskite solar cells on rigid substrates such as
glass, and they have exhibited PCE of 15.03% [116]. A separate study on a flexible paper substrate perovskite cell exhibited a maximum PCE of 2.7% [117]. The performance is notably lower than the glass substrate perovskite cell, but the paper device is mechanically flexible, low-cost, and on a recyclable substrate.

![Figure 20: Solar cell technology advancement of lab-based “hero chips” [121]](image)

### 2.3.6. Antennas

The development of flexible electronics has enabled research in flexible and printed antennas. The antenna is the most common device used for wireless communication, and, without a flexible antenna, a wireless system may as well be deemed useless. Conventional antennas are typically fabricated on a specialized radio frequency (RF) material, such as FR-4, that does not satisfy the conformal demands of flexible electronics. Antennas have been demonstrated on a wide range of substrates that have fair RF metrics. Metrics that have the
The most immediate effect on antenna performance are the loss tangent ($\tan \delta$), also called dissipation factor; and dielectric constant ($\varepsilon$), also called permittivity. The loss tangent is a measure of how lossy a dielectric is proportional to frequency. A desirable loss tangent is zero meaning that there is no loss due to the dielectric material. The dielectric constant is a measure of how much electrical charge a dielectric can store in an area and is a product of the vacuum permittivity ($\varepsilon_0 = 8.8542 \times 10^{-12} \dfrac{F}{m}$) and the relative permittivity ($\varepsilon_r$). The $\varepsilon_r$ of air is 1.0006 and the $\varepsilon_r$ within some supercapacitors is $10^5$ [118]. Flexible antennas have been fabricated on substrates such as photopaper ($\varepsilon_r = 3$, $\tan \delta = 0.07$) [119], liquid crystalline polymer (LCP) ($\varepsilon_r = 3$, $\tan \delta = 0.025$) [119], and Kapton ($\varepsilon_r = 3.5$, $\tan \delta = 0.002$) [120]. For printing antenna traces, Ag NP inks are commonly chosen due to their high conductivity.

Today’s modern devices support 2G, 3G, WLAN, GPS, and 4G-LTE standards which calls for multiband devices on substrates. A demonstration of an inkjet-printed, multiband antenna was performed in [120] with radiating elements centered at 1.2, 2.0, 2.6, and 3.4 GHz respectively which enabled the devices to cover GSM 900, GPS, UMTS, WLAN, ISM, Bluetooth, LTE 2300/2500 and WiMAX standards. Figure 21 illustrates the antenna design as well as $S_{11}$ scattering parameters. The printability of these devices allows dimensions to be easily scaled to operate at their designed frequencies with their respective radiation patterns.
Another application of conformal antennas is in sensors. Radio Frequency Identification (RFID) has enabled the design of sensor arrays that communicate signals via RFID transmission. An example of this technology is an RFID-based microfluidic cell that may be used to sense water quality as well as become a fluidic-tunable RF device [45]. The microfluidic substrate was a cast acrylic sheet of poly(methyl-methacrylate) (PMMA) in which the fluidic cavities were laser etched. The substrate for the antenna was paper, and Ag NP ink was chosen for antenna trace printing. The fluid was passed through a capacitive element on the RFID device, and the resonance of the circuit was shifted accordingly. Water, hexanol, ethanol, and ethanol-water solutions were measured in terms of $S_{11}$, and the results of this test are shown in Figure 22. An image of the microfluidic device is shown in Figure 23.
Figure 22: Results of water, ethanol, and hexanol test of water quality sensor [45]

Figure 23: Microfluidic RFID system [45]

2.4. **Instruments**

This segment introduces the measurement tools used to obtain the data in this thesis. Details such as instrument capabilities and features that were used in this thesis are introduced.
2.4.1. **Agilent E4980A Precision LCR Meter**

The LCR meter was used to measure the capacitance, inductance, and resistance of the passive electronic devices. This meter can produce frequencies from 20 Hz to 2 MHz as well as recording a sweep of 201 data points of various units. For example, the capacitor was performance tested from 100 kHz to 2 MHz, and the results of the sweep were plotted using Microsoft Excel. Due to the extremely small capacitances of the devices discussed in this thesis, proper calibration, corrections, and setup of this device were of higher priority than for any other instrument. For device testing in this thesis, the LCR meter was set up with four-terminal probes connected as close to the source (headers) as possible. Test leads were kept to an approximate 8 inches to reduce the test path and the amount of noise that may be produced by longer test leads. The LCR meter also features an auto-calibrate feature that measures the open-circuit and short-circuit parameters within the meter without any test load connected, and the collected data is used to mitigate any parasitic parameters within the device itself. Another correction feature on the LCR meter is the cable correction factor in lengths of zero, one, two, or four meters. In cases where measurements are slightly choppy and where the need for precise, small-value measurements, such as picofarads, are required, different time modes are available: short, medium, and long.

On top of the above error corrections, the LCR meter utilized series and parallel circuit modes to approximate inductance and capacitance. For the work in this thesis, the parallel circuit mode was chosen for the capacitor measurements, and the series circuit mode was chosen for inductor measurements. The parallel circuit mode for capacitors was chosen because the small capacitance yields large reactance causing the parallel resistance to have greater effect on the impedance than the series resistance. The left image in Figure 24 illustrates a small capacitor effect, while the right image illustrates a large capacitor effect. The measurement of inductors was performed with the series circuit model because the reactance of a small inductor is small causing the series resistance to have greater effect on the impedance.
The right image in Figure 25 illustrates the small inductance circuit effect and the left image illustrates the large inductance circuit effect. When measuring these devices, the automatic range feature was disabled, and manual selection of the range was selected. This setting significantly affected the measurement stability causing it to stabilize to 2 decimal places for the capacitors, and three decimal places for the resistors and inductors.

Figure 24: Small capacitor mode (left) and large capacitor mode (right) [121]

Figure 25: Large inductor mode (left) and small inductor mode (right) [121]
2.4.2. **Agilent 34401A Digital Multimeter**

The 34401A Multimeter was the primary device used to characterize sheet resistance on various substrates as well as characterize the bend sensor. This meter can perform voltage, current, short/open-circuit, and 2/4-terminal resistance measurements. The meter may also measure these parameters in AC or DC. To measure the sheet resistance, the meter was set up in 4-terminal configuration and connected to the test plate shown in Figure 39, and the units derived from this measurement were in ohms (Ω). The two-terminal configuration was used to perform measurements to characterize the bending sensor. All measurements performed with this device were performed under the automatic range setting.

2.4.3. **Agilent E3630A Triple Output DC Power Supply**

The triple output DC power supply was used to supply the +/- 15 V to the LM741 operational amplifier used in the bend sensor circuit in section 5.1. This device is capable of outputting +/- 20 V by utilizing three terminals: (+) V, (-) V, and common. By connecting these terminals in series, a 0-40 V potential is possible with 0.5-amp current supply. There is also a third terminal capable of outputting + 6 V with respect to common with 2.5-amp current supply. A chassis ground terminal is also accessible on the front panel for applications that require chassis ground.

2.4.4. **Agilent E3633A DC Power Supply**

This power supply was adjusted using the digital oscilloscope to supply 5 V precision down to three decimal places to the bend sensor circuit. There are two options for power output on this power supply: 8V/20A or 25V/7A. There are current and voltage limits down to three decimal places for circuit protection, and constant current and constant voltage modes are also available as settings on this device. The power supply has digital on/off control of the output allowing output control without powering off or touching of wires. This device was used in the
8V/20A range with voltage set at 5 V and over-current protection set at 1 A to supply a precision 5 V to the bend sensor circuit.

2.4.5. **Tektronix TBS1102B-EDU Digital Oscilloscope**

This device is a digital oscilloscope with the functionality of other typical oscilloscopes but has a focus toward educational applications. The oscilloscope has 100 MHz bandwidth with a 2 GS/s sample rate. There are two channels that may be used to read the amplitude, frequency, mean, peak-to-peak, etc. voltage and current. The oscilloscope is capable of logging digital output for plotting results in programs such as Microsoft Excel or Matlab. In this thesis, the oscilloscope was used to measure the mean voltage of channels one and two. Channel one was connected to the output of the bend sensor differential amplifier circuit, and channel two was connected across the sense resistor of the bend sensor circuit. This connection provided a vantage point on both the small-signal voltage reading as well as the amplified differential voltage output. It was for this reason that a two-channel oscilloscope was chosen for voltage measurements rather than a series of volt-meters.
CHAPTER 3: PROCESS DEVELOPMENT

3.1. Pattern Design

Following the selection of substrate and inks for printing, designing a pattern to print is perhaps the next step in printing a pattern with the Fujifilm DMP-2830. Designing patterns may be performed using multiple software programs that are commercially available. In this thesis, Adobe Illustrator and the default Fujifilm Dimatix Pattern Editor were the software programs of choice for designing patterns to print.

The Pattern Editor is software located in the “Tools” drop down menu within the Drop Manager software which is used to operate the DMP-2830. Within this software, critical printing metrics are selected such as drop spacing, pattern array, substrate dimensions, and number of layers to print. The primary purpose of the Pattern Editor is to design, create, and edit patterns with very precise attention to drop sizing and position on a pattern. Figure 26 shows a screenshot of the Pattern Editor where patterns are created. To create a pattern, a few immediate parameters need to be entered: the substrate dimensions, drop spacing, and number of layers. The Pattern Editor is only capable of entering rectangular features, therefore, drawing round edges requires auxiliary software such as Illustrator. Once entering drop dimensions and location within the Pattern Editor, the Preview Drops window is used to analyze the drop size and feature sizes of the pattern. Figure 26 shows a screenshot of the Preview Drops screen where pattern features are discernable by black lines and drops are discernable by blue circles. Patterns designed in this software may be printed directly with the Drop Manager without any file conversion. Files created with the Pattern Editor are file extension .ptn.

An important observation to be made is that the drops will completely fill the pattern traces, indicated by a black line, as well as overwhelm the pattern traces at times. For best printing results, designs should consider the fact that droplets will inherently be overwhelming desired trace dimensions by small amounts. The case of Figure 26 displays approximately 60% of an entire droplet overwhelming the pattern traces.
The other software used for pattern design was Adobe Illustrator, a popular drawing software for artists and designers. Illustrator supports the drawing of many features from boxes and circles to lines and squiggles. Using these features, more advanced patterns may be produced, for example using concentric circles to create a circular planar inductor. Though designing patterns in Illustrator is much simpler than using the Pattern Editor, there are more steps involved in converting a pattern designed in Illustrator to a pattern that is compatible with the Drop Manager. To design a pattern, the drops per inch (ppi) should be noted by using the Image to Pattern Converter, also called the Pattern Editor (Bitmap images), located in the “Tools” drop down menu. The Image to Pattern Converter is like the Pattern Editor, but it lacks the interface to add additional rectangular features to the Illustrator pattern. To change the PPI, input a drop spacing, and the “DPI” will appear in parenthesis above the text window. Figure 27 displays a screenshot of the Image to File Converter.
The input file to the Image to Pattern Converter needs to be a single layer bitmap file which is a setting available in the export feature found in the “File” drop down menu. Once the Export screen is open, the file name and file extension (.bmp) can be chosen. The next step in Illustrator is in the Rasterize Options window, shown in Figure 28, where the color model (bitmap), resolution (other, input ppi value), and anti-aliasing (art optimized) settings are located. The next step in file conversion is to open the bitmap file in the Image to Pattern Converter where the image is saved as a printable .ptf file. These steps are critical in achieving the desired printing results. For example, if the drop DPI on the Image to Pattern Converter and ppi on Illustrator are not the same, the file will not convert with the same dimensions.
3.2. Cartridge Filling and Maintenance

The DMP-2830 utilizes interchangeable print cartridges that are mounted with a snap fastener to the print carriage. The cartridge assembly is comprised of the fluid module, where ink is stored, and jetting module, where print head is housed. The capacity of the cartridge is noted as 1.5 mL in the user manual, but cartridges with Novacentrix JS-B25HV and JS-B40G Ag NP inks were filled to 3.0 mL with no adverse effects. Over-filling the cartridge was tested to reduce the waste from disposing used cartridges and filling new cartridges. This permitted the same cartridge to be used nearly twice the amount of the designed life, in turn, allowing for more cost-effective prototyping.

Filling cartridges is a simple task but is not to be sold short. To reduce the amount of waste and potential for mess in filling a cartridge, care must be taken. Filling is performed using a syringe, filter (when needed), and provided fill needle. The cartridge is filled by inserting the needle into the fill tube on the bottom of the cartridge and depressing the syringe plunger. When filling a cartridge, air struggles to escape from the fill tube causing relatively large pressure to build up in the fluid sac. To relieve this pressure, the syringe should be fully removed every 0.5 mL or less and re-inserted. This relieves pressure and the risk for large ink bubbles to form at the entrance of the hole that usually pop and seep ink on frequently touched areas of the
cartridge. Once filled at desirable volume up to 3 mL, the needle may be removed, extra ink can be deposited back into its container, and the fluid module and jetting module can be snapped together.

If a single cartridge is to print for multiple days with printer shut-off times in between, it is important to care for the cartridge properly. After printing, there will be excess ink on the white drop viewing sticker directly near the print head at the bottom of the cartridge. This ink may be rinsed off with very lightly with water from a lab bottle or wiped off with a heavily moistened Kim Wipe. If rinsing with water, avoid tipping the cartridge upside-down; water will enter the nozzles and could contaminate the cartridge ink. If wiping with a Kim Wipe, the cartridge may be tipped upside-down, but the print head must not be touched.

Storing the cartridge is critical as well but varies for different inks. For JS-B40G Ag NP ink, the best results were achieved when the cartridge was stored inside of the DMP-2830 with nozzles facing down and propped up on two glass slides to keep the nozzles from contacting any surface. For JS-B40G Ag NP ink, the best results for daily printing were achieved when the cartridge was stored upside-down inside the DMP-2830. For printing with many days between, a cartridge shaker was required to lightly gyrate the cartridge and keep the ink from settling or drying in the nozzles.

3.3. Waveform Editor

The waveform editor provides access to create and edit voltage waveforms that control the jets in the print head. The waveform is a feature that increases the range of fluids that are compatible with the Dimatix print heads. The waveform has four regions that control the position of the piezoelectric elements, each of them having a level, slew rate, and duration. The level is the percent of the amplitude set within the Cartridge Settings Screen, the slew rate is the rate at which the voltage ramps, and the duration is the amount of time (in µs) a segment occupies. Figure 29 shows a screenshot of the Waveform Editor with each segment separated by a
highlighted color. These segments are discussed below. The waveform in this image is dedicated to JS-B25HV ink.

Segment 1: This segment is the beginning of the jet pulse where the piezoelectric is in relaxed position. Here, fluid is pulled into the jetting chamber from the inlet. The meniscus at the nozzle is also pulled. Figure 30 illustrates the effect of this segment on the jetting chamber.
Segment 2: This segment is where the voltage ramps up to the maximum voltage to eject a droplet from the nozzle. Fluid flows out of the nozzle as well as back out of the inlet.

Figure 31: Segment 2 view [62]

Segment 3: This segment serves as an intermediate step to return to the standby state. The voltage is brought to a middle state to allow the fluid in the chamber to partially refill. This avoids stressing the meniscus to the point at which it collapses allowing air into the chamber.

Segment 4: This segment is the final portion of the waveform and is where the piezoelectric returns to a standby state while simultaneously filling the chamber slightly more. The meniscus is again pulled slightly but not enough for it to collapse. Figure 32 illustrates the relaxation of the piezoelectric to the standby state.

Figure 32: Segment 4 view [62]
For JS-B40G and JS-B25HV inks, the waveforms were provided by Novacentrix. No modification of the waveform was necessary to print effectively, thus, allowing for more rapid prototyping once receiving the ink.

3.4. **Drop Matrix**

The drop matrix is a set of drops that are used to select the appropriate drop resolution for each substrate. The substrate/ink interaction is not consistent between different substrates, and the simplest way to measure this characteristic is to print individual droplets and use the fiducial camera mounted on the print carriage to measure the drop sizes. A square drop matrix with drop spacing of 150 µm was designed using the Pattern Editor. Since 150 µm is large relative to an individual drop, the drops will be separated by large distance from each other making droplets easily distinguishable. Figure 33 shows fiducial camera screenshots of JS-B25HV Ag NP droplets on the Novacentrix Novel IJ-220 substrate as well as JS-B40G Ag NP droplets on a glass microscope slide.

![Figure 33: Droplets of JS-B40G on glass (left) and JS-B25HV on Novele PET (right)](image)

Measuring the drop sizes on the DMP-2830 can be done by clicking on opposite edges of the drops; the diameter will be displayed in the fiducial camera window. For each substrate, three diameter measurements of different droplets were averaged for selecting the proper
resolution. Table 1 and Table 2 display the drop sizes for each substrate tested in this thesis. Note that all substrates were at room temperature and humidity when printing.

<table>
<thead>
<tr>
<th>JS-B40G</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>Drop Size (µm)</td>
</tr>
<tr>
<td>Kapton</td>
<td>19</td>
</tr>
<tr>
<td>Novele PET</td>
<td>23</td>
</tr>
<tr>
<td>Photopaper</td>
<td>26</td>
</tr>
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<td>Paper PHD 230</td>
<td>38</td>
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<tr>
<td>Paper PHD 95</td>
<td>39</td>
</tr>
<tr>
<td>Paper PXD 200</td>
<td>57</td>
</tr>
<tr>
<td>PET (Novele reverse)</td>
<td>62</td>
</tr>
<tr>
<td>Glass</td>
<td>72</td>
</tr>
</tbody>
</table>

Table 2: Drop spacing on substrate using JS-B25 Ag NP ink

<table>
<thead>
<tr>
<th>JS-B25HV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>Drop Size (µm)</td>
</tr>
<tr>
<td>Novele PET</td>
<td>37</td>
</tr>
<tr>
<td>Photopaper</td>
<td>44</td>
</tr>
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<td>Kapton</td>
<td>46</td>
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<tr>
<td>Paper PHD 230</td>
<td>47</td>
</tr>
<tr>
<td>Paper PHD 95</td>
<td>47</td>
</tr>
<tr>
<td>Paper PXD 200</td>
<td>68</td>
</tr>
<tr>
<td>PET (Novele reverse)</td>
<td>100</td>
</tr>
<tr>
<td>Glass</td>
<td>&gt; 150</td>
</tr>
</tbody>
</table>

3.5. Surface Activation and Preparation

Substrates that do not have desirable printing performance may be modified to increase the substrate’s printing performance. There are numerous methods of “activating” the surface of a substrate, but the method chosen in this thesis is plasmonic activation using the Monarch CS-1701 Reactive Ion Etch. Substrates including glass, Kapton, and PET are all substrates whose
printing properties change as power level and time exposed to plasma are varied. Both JS-B40G and JS-B25HV inks were printed at various surface activations on each substrate.

The first ink used for testing surface activation was JS-B40G Ag NP ink. For glass, the power level was fixed at 125 W to achieve any activation, and, at this power level, the glass was exposed to plasma for 60 seconds. When glass was exposed to the oxygen plasma, the drop size decreased from approximately 73 µm to 62 µm. It may be possible to activate the surface further to decrease the drop size, but for printing on glass 62 µm was deemed sufficiently small. When activating PET, the power level was also fixed to 125 W to achieve sufficient etching. The substrate was exposed to plasma for 60 seconds to decrease the drop size from 62 µm to 36 µm. Kapton, however, reacted different than glass and PET when exposed to the oxygen plasma. When exposed to a 125 W oxygen plasma, the drop size increased from 19 µm to 70 µm. This result occurred because Kapton is intrinsically hydrophobic, and the plasmonic activation decreased the hydrophobicity. Glass and PET displayed the opposite; plasmonic activation increased hydrophobicity.

Next, JS-B25HV Ag NP ink was used for testing surface activation. Glass was not tested as a viable substrate for this ink due to its extreme hydrophilic surface interaction. Like the previous tests, PET was exposed to a 125 W oxygen plasma to decrease the drop size from 100 µm to 58 µm. Similar results to JS-B40G were obtained when printing JS-B25HV on Kapton. Kapton was exposed to a weaker plasma, 60 W, to increase the drop size from 46 µm to 75 µm. Again, in this test, the PET displayed hydrophobic reaction to plasmonic activation while Kapton displayed hydrophilic reaction to plasmonic activation.

While printing on glass, cleaning was critical for satisfactory printing results. Cleaning was performed in a four-step process using lab bottles to stream solvent onto the glass slide. The order of solvents used was in order as follows: acetone, ethanol, isopropanol, and de-ionized water. Figure 34 shows the difference between a cleaned, activated glass slide and uncleaned, activated glass slide. The cleaned glass slide provided good print results with
straight lines and square corners. Conversely, the uncleaned glass slide provided jagged edges with a significant amount of ink overflow. Overflow was when the ink bled past the feature definition; in the case of Figure 34, the overflowing feature would be the interdigital fingers of the capacitor.

![Image](image_url)

Figure 34: Interdigital capacitor when printed on clean, activated glass (left) vs unclean, activated glass (right)

3.6. Drop Overlap and Saber Angle

The drop overlap was selected as a percentage and represents the amount that one drop overlaps another. The drop overlap directly reflects the drop spacing to be used for printing which is different for every substrate. The drop spacing may be calculated using the equation

\[
\text{drop spacing} = \text{drop size} \times (1 - \text{percent drop overlap})
\]

The first drop overlap tested for every substrate was 20% which is shown with expected appearance in Figure 35. 20% drop overlap was deemed a good starting point for nearly complete drop overlap because drop sizes were taken as an average. From this point, printing performance could be increased by increasing the drop overlap. For example, if tiny voids are present in the printed traces then the drop overlap can be increased to fill those voids. The drop overlap was also increased to measure its effect on the sheet resistance, and these results are discussed within the Sheet Resistivity section.
The drop spacing was set by rotating the cartridge mounted on the print carriage to the appropriate angle (saber angle). Every drop spacing is related to a resolution and saber angle and is calculated using the equation $\text{drop spacing} = 254 \, \mu m \times \sin \theta$. Figure 36 illustrates the rotation of the cartridge to calculate the saber angle ($\theta$) given the drop spacing (DS) and print head nozzle spacing (254 $\mu$m). The rotation of the cartridge is maneuvered by hand which makes the adjustment a difficult task. The print carriage has micrometers for rough setting the cartridge. Since correct adjustment of the saber angle is critical, multiple measurements using the fiducial camera “Measure Cartridge Angle” tool is necessary. The most significant figure on the print carriage micrometer is 1/10th degree, but the measure cartridge angle tool indicates 1/100th degree significant figure which allows slightly more precise adjustment of the cartridge. Achieving consistent drop spacing with the measure cartridge angle tool proved to be difficult due to the “eying up” of the crosshairs. For this reason, a baseline error of 0.08° for three drop spacing measurements was accepted. All cartridge alignment measurements were performed.
by printing on Novele PET because it produced smaller drops, and the center of smaller drops was easier to locate.

Figure 36: Illustration of drop spacing derivation

3.7. Drop Speed

The drop speed can be modified by changing the voltage applied to the piezoelectric element through the Cartridge Settings window, and the physical drops may be viewed using the Drop Watcher. As specified by the user manual, the drop velocity should be set between 7-9 m/s. The drop velocity for JS-B25HV was set at 8 m/s while the JS-B40G was set at 6 m/s for the most uniform drop formation.

For optimal printing performance, each nozzle must be calibrated to contact the substrate simultaneously using the Drop Watcher. If drops are too slow, increasing the voltage will increase the velocity, and decreasing the voltage will decrease the velocity. Figure 37 shows a screenshot displaying droplets under the Drop Watcher camera jetting at 8 m/s.
Print priming is the printing of a “primer line” to ready the nozzles for printing the actual pattern. Without inserting the primer line, the pattern displayed jagged edges where the pattern was designed to have straight edges. The primer line nearly eliminated the jagged edges previously present in the non-primed patterns. Any feature printed past the first 0.5 mm of a pattern displayed satisfactory smooth edges. The primer line was inserted into the pattern file using the pattern editing software (Illustrator or Pattern Editor). A vertical line 100 µm in width and pattern size in height was inserted 3 mm before the pattern to create the primer line. Figure 38 shows microscope images of a pattern without the primer line versus printing a pattern with a primer line.
Figure 38: Non-primed pattern (left) vs. primed pattern (right)

3.9. **Sheet Resistivity**

To obtain sheet resistance \( R_S \) in units of ohms per square (\( \Omega/\text{sq} \)), the Van der Pauw (VDP) pattern was printed on glass, Novele PET, and photopaper. This pattern was used to measure resistance \( R_{ABCD} \) in units of ohms (\( \Omega \)) by implementing a four-terminal measurement technique. Two probes pass constant current while the other two probes are voltmeter probes. This technique was useful for eliminating errors due to measurement device losses such as cable loss. The constant current source supplies a constant current with lines that have some loss; this loss was acceptable because current is known and constant. The volt meter measures the voltage with an “infinite” internal impedance to diminish the current passing into the volt meter, hence, leading to a known voltage measurement with absence of parasitic resistance. Sheet resistance in units of \( \Omega/\text{sq} \) was calculated using the equation \( R_S = R_{ABCD} \frac{\pi}{\ln(2)} \) [59]. The goal of measuring sheet resistance was to determine the optimal printer settings, such as drop overlap and number of layers, that result in minimum sheet resistance. Figure 39 shows an image of the VDP pattern printed on glass being tested with a custom four-terminal probing tool whose test leads are connected to the Agilent 34401A Multimeter. Since printing occurs when the print carriage moves in the X-direction, two VDP sheet resistance measurements were taken which are indicated as orientation A and B. Orientation A is measurement “parallel” to the
direction of printing. Orientation B is measurement after rotating the sample 90 degrees for measurement “perpendicular” to the direction of printing. Figure 40 illustrates the probe contact with the VDP pattern. Probe connection to the multimeter are as follows: A to input high, B to input low, C to sense high, and D to sense low.

Figure 39: VDP pattern on PET with 4-terminal probing tool

Figure 40: Illustration of probes A, B, C, and D oriented on the VDP pattern. Orientation A (left) and orientation B (right)
Three metrics were varied to achieve different sheet resistivities: oven time, drop spacing, and number of layers. It was assumed that the sheet resistivity would decrease as each of these metrics was increased; for example, oven time increasing. These results are discussed below. The variation from orientation A to orientation B is also considered in the discussion of the results. This quantity was calculated as a percentage using the equation \[
\% = \frac{\text{current} - \text{original}}{\text{original}} \times 100
\] which resulted in the percentage of orientation A that orientation B was within. Three samples for each metric were printed and measured to indicate printing consistency.

### 3.9.1. Sheet Resistivity vs. Oven Time

The first test performed to decrease the sheet resistance on each substrate was to increase the exposure to heat by increasing the substrate’s oven time. Each sample was sintered in a vacuum oven at 25 mL Hg at 220 °C for JS-B40G and 85 °C for JS-B25HV. The drop overlaps for samples began at 20%. Samples were thermally sintered at various intervals in time until conductivity was achieved. If 20% overlap was not sufficient enough to achieve conductivity, then 30%, 40%, and so on, were chosen to increase drop overlap until conductivity was achieved.

JS-B40G was printed on glass, and consistent conductivity was achieved at 40% drop overlap. The sheet resistivity saturated at two hours at approximately 0.068 Ω/sq which is approximately 54% less than the original value of 0.150 Ω/sq. It was also observed that the sheet resistivities on glass for orientation A and B were very close. At 60 minutes, orientation B was within 9.47% of orientation A, and at 120 minutes, orientation B was within 7.35% of orientation A. This indicates that horizontal printing motion of the DMP-2830 has little effect on the sheet resistance on glass. Figure 41 displays the results of sheet resistivity vs. oven time for glass.
JS-B25HV was printed on Novele PET, and conductivity was achieved at 30% drop overlap. The sheet resistivity decreased as the time in oven increased. Unlike glass, orientation A and orientation B produced rather different results. At 5 minutes, orientation B was within 25.99% of orientation A, and at 25 minutes, orientation B was within 19.05% of orientation A. This result indicates that the horizontal printing motion of the DMP-2830 has larger effect on Novele PET than glass. It also indicates that, as the oven time increases, the sheet resistances of orientation A and orientation B slightly converge on each other. Per the data sheet for JS-B25HV, the resistivity, in µΩ-cm, using thermal processing on Novele PET saturates at 5 minutes of sintering at 100 °C. The difference between 5 minutes and 480 minutes of thermal sintering is only 0.4 µΩ-cm. For this reason, 25 minutes was the maximum time that Novele PET spent in the oven. Figure 42 displays the results of sheet resistivity vs. oven time for Novele PET.

Figure 41: Sheet resistivity vs. oven time on glass
JS-B25HV was then printed on photopaper, and conductivity was achieved at 40% drop overlap. Though 40% drop overlap produced conductive patterns, there was very little inconsistency, and the test resolution was chosen as 50% drop overlap. It was observed that the sheet resistance of orientation of A and B were closer than that of Novele PET but not as close as glass. At 5 minutes in the oven, orientation B was within 10.29% of orientation A, and at 25 minutes in the oven, orientation B was within 11.02% of orientation A. This result indicates that the horizontal printing motion of the DMP-2830 has smaller effect on the sheet resistance compared to Novele PET, and the increase in oven time does not necessarily cause the sheet resistance to converge. As described previously, 25 minutes was the longest time photopaper spent in the oven because JS-B25HV in was used. Figure 43 displays the results of sheet resistivity vs. oven time for photopaper.

Figure 42: Sheet resistivity vs. oven time on Novele PET
3.9.2. Sheet Resistivity vs. Drop Overlap

The second test performed to decrease sheet resistance was to increase the drop overlap, therefore, decreasing drop spacing. This test was performed with JS-B25HV and JS-B40G ink on glass, Novele PET, and Photopaper. The samples were thermally sintered in a vacuum oven pumped down to 25 mL Hg at 220 °C for JS-B40G and 85 °C for JS-B25HV. Note that in this section “consistent” results were achieved when all three printed samples were conductive.

JS-B40G was printed on glass at 20% starting overlap, and the overlap increased to 30% and then 40%. A cure time of 120 minutes at 220 °C were the chosen sintering parameters for the best result from the oven time test. It was observed that increasing drop overlap significantly decreased the sheet resistivity. It should be mentioned that 20% drop overlap resulted in one of three samples conducting and 30% drop overlap resulted in two of three samples conducting. For best printing performance, 40% drop spacing was chosen for pattern printing. The increase in drop overlap caused the sheet resistance decreased by 46.67% for
orientation A and 65.22% for orientation B. The sheet resistances of orientation A and B also converged on each other. At 20% drop overlap, orientation B was within 23.53% of orientation A, and at 40% drop overlap, orientation B was within 8.00% of orientation A. This result indicates that greater drop overlap on glass is desirable for reducing the effect of the DMP-2830's horizontal printing motion on the sheet resistance. Figure 44 displays the results of sheet resistivity vs. drop overlap on glass.

![Figure 44: Sheet resistivity vs. drop overlap on glass](image)

JS-B25HV was printed on Novele PET at 30% starting drop overlap, and the overlap increased to 40% and 50%. The starting point of 30% is where all three VDP patterns were consistently conductive, and 25 minutes at 85 °C were the chosen sintering parameters for the best result from the oven time test. It was observed that increasing the drop overlap decreased the sheet resistivity 54.05% for orientation A and 46.67% for orientation B. The increase in drop overlap also caused the sheet resistance to slightly converge. At 30% drop overlap, orientation B was within 19.05% of orientation A, and at 50% drop overlap, orientation B was within 5.19% of orientation A. Compared to longer sintering time, increasing drop overlap is much more...
effective at reducing the effect of the DMP-2830’s horizontal printing motion. Figure 45 displays the results from varying drop overlap on Novele PET.

![Graph: Sheet resistivity vs. drop overlap on Novele PET](image)

Figure 45: Sheet resistivity vs. drop overlap on Novele PET

JS-B25HV was then printed on photopaper with consistent sheet resistances beginning at 40% drop overlap, and the overlap increased to 50% and then 60%. It was observed that increasing the drop overlap decreased the sheet resistance like that of Novele PET. From 40% to 60% drop overlap, the sheet resistance decreased 53.49% for orientation A and 32.35% for orientation B. The increase in drop overlap also displayed converging sheet resistances, but these results were not as great as Novele PET. At 40% drop overlap, orientation B was within 21.03% of orientation A, and at 60% drop overlap, orientation B was within 14.29% of orientation A. Reducing the drop spacing is effective at reducing the effect of the DMP-2830’s horizontal printing motion but not as effective as increasing the number of layers. Increasing layers for print performance is described in the next section. Figure 46 displays the results of sheet resistivity vs. drop spacing on photopaper.
3.9.3. **Sheet Resistivity vs. Layers**

The final test performed to decrease the sheet resistance was to increase the number of layers printed. The DMP-2830 can complete a print and return to the print origin to begin a second, third, etc. layer without the user having to click “print” after every layer. This test as well was performed with JS-B25HV and JS-B40G ink on glass, Novele PET, and Photopaper. The samples were thermally sintered in a vacuum oven pumped down to 25 mHg at 220 °C for JS-B40G and 85 °C for JS-B25HV. Again, note that in this section “consistent” results mean that all three printed samples were conductive.

JS-B40G was printed on glass at 20% drop overlap because it was observed that, as ink volume on the substrate increased, the droplets joined together to form a single film with very little indication that the print was done using a horizontal printing motion. Still noting that 20% drop overlap produced one of three conductive patterns, the case changed for printing multiple layers on glass. Once multiple layers were printed, the samples were consistently conductive. It was observed that increasing the number of layers decreased the sheet resistance as much as
increasing the drop spacing. In four layers, the sheet resistance decreased 80.00% in orientation A and 73.91% in orientation B. Increasing the number of layers also caused the sheet resistances in orientation A and orientation B to become nearly equal on all three patterns compared to the initial separation (at 46 µm and one layer) being 23.53%. For reducing sheet resistance and the effect of the DMP-2830’s horizontal printing motion, printing multiple layers on glass is the best option. Figure 47 displays the results of sheet resistivity vs. layers printed on glass.

![JS-B40G Glass, 46um, 220C](image)

**Figure 47:** Sheet resistivity vs. layers printed on glass

JS-B25HV was printed on Novele PET at 30% drop overlap. 30% drop overlap was chosen was due to the rapid rate at which the DMP-2830 exhausted the ink in a cartridge. To conserve ink, only conducting patterns were desired for printing and testing on Novele PET. It was observed that increasing the number of layers printed on Novele PET significantly decreased the sheet resistance, 54.05% in orientation A and 62.50% in orientation B. Increasing the number of layers also promoted the sheet resistances in orientation A and B to tightly converge with only 8.47% difference in orientation B from orientation A. Compared to increasing
oven time and increasing drop overlap, increasing the number of layers printed on Novele PET is the most effective setting for producing low resistivity and little deviation between orientation A and orientation B. Figure 48 displays the results of sheet resistance vs. layers printed on Novele PET.

![JS-B25HV Novele, 26um, 85C](image)

**Figure 48: Sheet resistivity vs. layers printed on Novele PET**

JS-B25HV was then printed on photopaper at 50% drop overlap. Like the layer test on Novele PET, 50% drop overlap was also chosen to print only quality patterns and conserve ink. The increase in number of layers printed on photopaper resulted in substantial decrease in sheet resistance. Orientation A decreased 66.67% and orientation B also decreased 66.67%. The sheet resistivities in orientation A and B converged to 8.88% which is similar difference to increasing the time in the oven. What makes increasing oven time and number of layers different is that the oven time increase only decreased the sheet resistance approximately 7% where increasing the number of layers decreased sheet resistance approximately 67%. This observation shows that increasing the number of layers is the most effective method in reducing
the sheet resistance on photopaper. Figure 49 displays the results of sheet resistance vs. layers printed on photopaper.

![Sheet resistivity vs. layers printed on photopaper](image)

**Figure 49: Sheet resistivity vs. layers printed on photopaper**

### 3.9.4. Conclusion on Sheet Resistance

Sheet resistance was affected by varying the following parameters: drop overlap, oven time, and layers printed. Each substrate displayed different results for each test, but the parameter that most effects the sheet resistance is the number of layers printed. Increasing the number of layers significantly decreased the sheet resistance which is clearly identifiable on glass where an 80% decrease was observed. Increasing the number of layers printed also promoted the sheet resistivities of orientation A and B to converge on each other. This result indicates that adding more layers causes the sheet resistance to be less effected by the horizontal print motion of the DMP-2830.
CHAPTER 4: PRINTED PASSIVE COMPONENTS

This chapter reviews results from the printing of resistors, capacitors, and inductors on glass, Novele PET, and photopaper. JS-B40G was printed on glass and thermally sintered at 220 °C, and JS-B25HV was printed on Novele PET and photopaper and thermally sintered at 85 °C. All samples were sintered in the vacuum bake oven which was pumped to 25 mL Hg. The purpose of this chapter is to reveal the effects of varying parameters such as line width, length, gap size, number of turns, diameter, etc. on the resistance, capacitance, and inductance.

4.1. Resistors

Resistors were printed on each substrate (glass, Novele PET, and photopaper) to analyze their printability. Parameters such as length and width were varied over three resistor constructions. On glass, the resistor was printed at 60% drop overlap which corresponds to 26 µm drop spacing. On Novele PET and photopaper, the drop overlap chosen was 50% which corresponds to 18 µm and 22 µm drop spacing for Novele PET and photopaper respectively. Greater drop overlap was chosen to reduce the effect of the horizontal printing motion when printing the tall meandering resistor. The resistor constructions were of straight line, zig-zag, and meander which are described in detail below. Three of each pattern was printed for showing repeatability. The impedance of each resistor was measured using the Agilent E4980A Precision LCR meter at 1 kHz. Printing resistors has application in electrical circuits as well as in sensing. In this thesis, the resistor is used as a bend sensor that measures strain and deflection depending on which direction the substrate is bent.

4.1.1. Straight-line Resistor

The straight-line resistor was the first resistor printed and was designed as a line with 3 mm x 3 mm contacts printed on the ends. This resistor was printed in 10 mm, 20 mm, and 30 mm lengths and was the main test subject for increasing the line width at widths of 150 µm, 300
µm, and 450 µm. The straight-line resistor was drawn using the Pattern Editor, and a photo of a 150 µm x 10 mm resistor is shown in Figure 50.

![Microscope image of straight-line resistor on photopaper](image)

Figure 50: Microscope image of straight-line resistor on photopaper

The straight-line on glass provided linearly increasing results, 5.24 Ω at 10 mm to 15.137 Ω at 30 mm, as the line length increased. These values correspond to a slope of 0.495 Ω/mm which is the smallest straight-line slope compared to Novele PET and photopaper. This means as lines on glass increase, the resistance will rise slower than on Novele PET and photopaper. Figure 51 displays the results of increasing the line length. The resistance also decreased exponentially, 10.17 Ω at 150 µm to 4.139 Ω at 450 µm, when increasing the line width. Figure 52 displays the results of increasing the line width. The repeatability test of the straight-line resistor provided a standard deviation of 0.019 Ω and mean resistivity of 15.142 Ω. Table 3: Straight-line resistance on glass, repeatability test

Table 3 displays the results of the straight-line repeatability test.
As the line length increased, the straight-line resistor on Novele PET produced linearly increasing resistance from 10.249 Ω at 10 mm to 29.378 Ω at 30 mm which indicate a slope of
0.956 Ω/mm. This slope is greater than both glass and photopaper and causes Novele PET to become less ideal of a substrate when printing lengthy metal traces. Figure 53 shows the results of increasing the line length on Novele PET. When increasing the line width, the resistance decreased at an exponential rate from 19.967 Ω at 150 µm to 7.143 Ω at 450 µm. The results from this test are shown in Figure 52. The straight-line resistor on Novele PET also produced repeatable results with a standard deviation of 0.694 Ω and average resistance of 30.125 Ω. Results from the reliability test are shown in Table 4.

Figure 53: Straight-line resistance on Novele PET, resistance vs. length

Figure 54: Straight-line resistance on Novele PET, resistance vs. width
Table 4: Straight-line resistance on Novele PET, repeatability test

<table>
<thead>
<tr>
<th>Trial</th>
<th>Resistance (Ω)</th>
<th>Phase (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29.378</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>29.947</td>
<td>0.05</td>
</tr>
<tr>
<td>3</td>
<td>31.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

The straight-line resistor on photopaper displayed linearly increasing resistance, from 10.56 Ω at 10 mm to 27.61 Ω at 30 mm, as the line length increased. The slope of this line is approximately 0.8525 Ω/mm. Figure 55 displays the results from this test. When varying the width, the resistance was reduced exponentially like on glass and Novele PET. Figure 56 displays the effect of increasing line width on photopaper. Printing the straight-line pattern on photopaper also produce repeatable results with standard deviation of 0.134 Ω with an average resistance of 27.500 Ω. Table 5 displays the results of the repeatability test on photopaper.

Figure 55: Straight-line resistance on photopaper, resistance vs. length
Table 5: Straight-line resistance on photopaper, repeatability test

<table>
<thead>
<tr>
<th>Trial</th>
<th>Resistance (Ω)</th>
<th>Phase (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27.614</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>27.312</td>
<td>0.05</td>
</tr>
<tr>
<td>3</td>
<td>27.575</td>
<td>0.05</td>
</tr>
</tbody>
</table>

4.1.2. Zig-Zag Resistor

The zig-zag resistor was the second resistor printed and was designed as a series of 5 mm lines connected at 45° angles with 3 mm x 3 mm contacts printed on the ends. For dimensions of this resistor, the length is the sum of all 150 µm line components of the resistor. The zig-zag resistor has potential to reduce the real estate that a planar resistor may consume which may be useful in miniaturizing printed circuits. This resistor was printed in 10 mm, 20 mm, and 30 mm lengths. The zig-zag resistor was drawn using Illustrator, and a microscope image of a 20 µm resistor is shown in Figure 57.
The zig-zag resistor on glass provided linear results when increasing the length of the resistor with resistance of 4.397 Ω at 10 mm to 13.017 Ω at 30 mm. This resistor printed on glass shows a slope of 0.431 Ω/mm which is less than the slope of the straight-line resistor. Figure 58 displays the results of increasing the line length on glass. The repeatability test provided a standard deviation of 0.040 Ω with an average resistance of 12.977 Ω. Table 6 displays the results from the repeatability test on glass.
Table 6: Zig-zag resistance on glass, repeatability test

<table>
<thead>
<tr>
<th>Trial</th>
<th>Resistance (Ω)</th>
<th>Phase (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.017</td>
<td>0.03</td>
</tr>
<tr>
<td>2</td>
<td>12.992</td>
<td>0.03</td>
</tr>
<tr>
<td>3</td>
<td>12.923</td>
<td>0.03</td>
</tr>
</tbody>
</table>

The zig-zag resistor on Novele PET also displayed linearly increasing resistance which is shown in Figure 59. The resistance increased from 9.53 Ω at 10 mm to 30.03 Ω at 30 mm which corresponds to a slope of 1.025 Ω/mm. The results for this test are shown in Figure 59.

The repeatability test for the zig-zag resistor printed on Novele PET exhibited fair repeatability with standard deviation of 0.337 Ω and average resistance of 30.365 Ω. Repeatability test results are displayed in Table 7.

Figure 59: Zig-zag resistance on Novele PET, resistance vs. length

Table 7: Zig-zag resistance on Novele PET, repeatability test

<table>
<thead>
<tr>
<th>Trial</th>
<th>Resistance (Ω)</th>
<th>Phase (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30.026</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>30.246</td>
<td>0.05</td>
</tr>
<tr>
<td>3</td>
<td>30.824</td>
<td>0.05</td>
</tr>
</tbody>
</table>
The zig-zag resistor on photopaper also demonstrates linear resistance response to increasing length. The resistance increases from 8.86 $\Omega$ at 10 mm to 26.05 $\Omega$ at 30 mm which corresponds to a slope of approximately 0.860 $\Omega$/mm. The results on resistance vs. increasing line length is shown in Figure 60. The repeatability test performed on the zig-zag resistor printed on photopaper showed that photopaper is capable of reproducing resistances with a standard deviation of 0.148 $\Omega$ and average of 26.256 $\Omega$. These test results are shown in Table 8.

![Zig-Zag Photopaper, Length](image)

Figure 60: Zig-zag resistor on photopaper, resistance vs. length

<table>
<thead>
<tr>
<th>Zig-Zag on Photopaper, Length = 30 um, Width = 150um</th>
<th>Resistance (Ω)</th>
<th>Phase (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>26.054</td>
<td>0.05</td>
</tr>
<tr>
<td>Trial 2</td>
<td>26.31</td>
<td>0.05</td>
</tr>
<tr>
<td>Trial 3</td>
<td>26.403</td>
<td>0.05</td>
</tr>
</tbody>
</table>

4.1.3. **Meander Resistor**

The meander resistor was the final resistor printed which consists of a trace of multiple 150 $\mu$m width lines connected by 90° angles. The lengths of the meander resistor are measured as the vertical extensions of the resistor and not the overall length of the resistor. This pattern
may also be used to reduce the real estate consumed per resistive component as well as perform as a resistive sensing device. An image of a 10 mm meander resistor is shown in Figure 61. Note that the slope of this line cannot be directly related to the straight-line or zig-zag resistor slopes due to the dissimilar overall line lengths of the meander resistor to the others.

![Image of a 10 mm meander resistor](image.png)

Figure 61: Microscope image of meander resistor on photopaper

The meander resistor on glass provided linear results of 36.74 Ω at 10 mm to 97.07 Ω at 30 mm with a slope of 3.016 Ω/mm. Figure 62 shows the results for the meander resistor on glass. The printing of this pattern is not reliable when the longest lines are perpendicular to the motion of the print head. Table 9 shows the results of the repeatability test of this meander resistor. Two of three patterns were conductive for this test which led to testing the effect of orientation on resistance. This test is performed in 4.1.3.1 Effect of Orientation on Resistance.
Figure 62: Meander resistance on glass, resistance vs. length

Table 9: Meander resistance on glass, repeatability test

<table>
<thead>
<tr>
<th>Trial</th>
<th>Resistance (Ω)</th>
<th>Phase (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>97.07</td>
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<tr>
<td>2</td>
<td>101.82</td>
<td>0.036</td>
</tr>
<tr>
<td>3</td>
<td>Non-conductive</td>
<td>Non-conductive</td>
</tr>
</tbody>
</table>

The meander resistor on Novele PET displayed linearly increasing resistance from 74.47 Ω at 10 mm to 238.94 Ω at 30 mm corresponding to a slope of 8.223 Ω/mm. Results from this test are shown in Figure 63. Table 10 displays the results from the repeatability test for the meander resistor printed on Novele PET. The meander resistor on Novele PET produced fair repeatability results with a standard deviation of 1.375 Ω and average resistance of 238.941 Ω. The standard deviation of the meander resistor on Novele PET may be significantly greater than the zig-zag and straight-line resistor on Novele PET, but the overall line length of the of the meander resistor is significantly greater than the straight-line and zig-zag resistor. Increasing line length of the vertically-oriented meander resistor compounds the deviation from shorter line to longer line as observed in this experiment.
Figure 63: Meander resistor on Novele PET, resistance vs. length

Table 10: Meander resistor on Novele PET, repeatability test

<table>
<thead>
<tr>
<th>Trial</th>
<th>Resistance (Ω)</th>
<th>Phase (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>238.9439</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>237.255</td>
<td>0.04</td>
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<tr>
<td>3</td>
<td>240.624</td>
<td>0.05</td>
</tr>
</tbody>
</table>

When printed on photopaper, the meander resistor produced the expected linearly increasing resistance as the leg length increased. The resistance increased from 64.84 Ω at 10 mm to 202.68 Ω at 30 mm which corresponded to a line slope equal to 6.892 Ω/mm. The meander resistor on photopaper also displayed the same results as Novele PET with fair repeatability. The standard deviation was 1.555 Ω and the average resistance was 201.045 Ω.
Figure 64: Meander resistor on photopaper, resistance vs. length

Table 11: Meander resistor on photopaper, repeatability test

<table>
<thead>
<tr>
<th>Trial</th>
<th>Resistance (Ω)</th>
<th>Phase (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
<td>198.954</td>
<td>0.05</td>
</tr>
<tr>
<td>3</td>
<td>201.499</td>
<td>0.04</td>
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</tbody>
</table>

4.1.3.1. Effect of Orientation on Resistance

This test was performed to examine the effect on the pattern orientation relative to the direction of the DMP-2830’s print head motion. A meander resistor was printed on glass with the longest component oriented in the horizontal direction, the same direction as the print head movement. The chosen resolution was 26 µm, the same resolution chosen for the resistance tests above, which was aimed at producing results under the same fabrication parameters with only pattern orientation changed. Three resistors were printed, and the result was that all three were functioning devices. The results from this test are shown in Table 12. The horizontal meander resistor provided a standard deviation of 0.098 Ω and average resistance 91.723 Ω. These results test show that the orientation of the pattern does matter when printing very thin, long lines. Comparing the standard deviations of the meander resistor printed on Novele PET
and photopaper to the standard deviation the meander resistor printed on glass, it may be observed that orienting the longest meander resistor component in the horizontal direction will reduce the standard deviations when printed on Novele PET and photopaper as well. For best results, the longest dimensions should be oriented along the path that the print head travels, the x-direction (horizontal).

Table 12: Horizontal meander resistances on glass, repeatability test

<table>
<thead>
<tr>
<th>Trial</th>
<th>Resistance (Ω)</th>
<th>Phase (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>91.603</td>
<td>0.036</td>
</tr>
<tr>
<td>2</td>
<td>91.842</td>
<td>0.036</td>
</tr>
<tr>
<td>3</td>
<td>91.73</td>
<td>0.036</td>
</tr>
</tbody>
</table>

4.2. Capacitors

Capacitors were also printed on glass, Novele PET, and photopaper and picofarad capacitances were obtained. Printing was performed on glass at 50% drop overlap which corresponds to approximately 36 µm drop spacing on a cleaned glass slide. Novele PET was printed at 30% drop overlap which corresponds to 26 µm drop spacing, and photopaper was printed at 50% drop overlap which corresponds to 22 µm drop spacing. The capacitor structure chosen for testing was the interdigital capacitor due to its common application in sensing devices. An image of the interdigital capacitor printed on Novele PET is shown in Figure 65. Parameters such as gap size, width, length, and number of fingers were varied over each substrate, and the capacitance and phase were recorded and are discussed below. The impedance ($Z_T$) and phase ($\theta$) of each capacitor was measured using the Agilent E4980A Precision LCR meter at 2 MHz. As noted in the Instruments section, the parallel circuit model was used to measure the printed capacitors. The capacitance ($C$) was calculated with the recorded $Z_T$ and $\theta$ using the equation $C = \frac{\sin\theta}{2\pi f Z_T^*}$.
The standard test procedure included the varying of the gap size, width, length, and number of fingers as mentioned above. For comparison purposes, the parameters values over each substrate did not change. For the gap test, the capacitor was constructed of three 150 µm width, 5 mm length lines, and the gap increased from 150 µm to 350 µm. For testing the effect of line length, the capacitor was constructed of three 150 µm width, 150 µm gapped lines, and the length increased from 5 mm to 15 mm. For the width test, the capacitor was constructed of three 5 mm length, 150 µm gapped lines, and the width increased from 150 µm to 350 µm. The capacitor under the finger test was performed with a 150 µm width, 150 µm gapped, 5 mm length capacitor, and number of fingers increased from three to five.

4.2.1. Capacitors on Glass

The capacitors printed on glass produced the largest capacitances compared to both Novele PET and photopaper substrates with the highest capacitance being 3.861 pF because of its relatively high dielectric constant. When varying the gap size of the capacitor, it was
observed that no capacitor printed at a gap size of 350 µm or greater could contain any charge, therefore making the component an open circuit rather than a capacitor. An increase in gap size decreased the capacitance, as expected. The results from this test are shown in Figure 66. The capacitance of the interdigital capacitor printed on glass was most effected by increasing the line length. Results from this test are shown in Figure 67. The line length was increased from 5 mm to 15 mm and the capacitance increased linearly from 1.936 pF to 3.861 pF with a slope of 0.192 pF/mm. Increasing the line width on glass provided samples with increasing capacitance, but results show that the capacitance will saturate at some point with increasing line width. These results are shown in Figure 68. Another method for increasing capacitance was to increase the number of fingers. Increasing the number of fingers caused the capacitance to increase linearly from 1.936 pF with 3 fingers to 2.750 pF with 5 fingers. The slope of this line was 0.407 pF/finger which is plotted in Figure 69. For every capacitor printed on glass, the phase angle never fell below -89.37° indicating that capacitors on glass are have low resistivities compared to the capacitance at 2 MHz.

Figure 66: Capacitor on glass, capacitance and phase vs. gap size
Figure 67: Capacitor on glass, capacitance and phase vs. line length

Figure 68: Capacitor on glass, capacitance and phase vs. line width
4.2.2. Capacitors on Novele PET

The capacitors printed on Novele PET produced the smallest capacitance due to its relatively low dielectric constant; the highest capacitance achieved in the standard test procedure was approximately 1.96 pF. The gap test on Novele PET revealed that increasing the gap size from 150 µm to 350 µm did not affect the capacitance greatly. This result indicates that, at these dimensions, the gap size does not affect the capacitance much. For significant decreases in capacitance, greater gap variations should be designed into the capacitor such as creating a 50 µm gap to increase the capacitance or creating a 500 µm gap to decrease the capacitance. Results from this test are plotted in Figure 70. Again, the greatest increase in capacitance was seen when increasing the line length. The capacitance increased from 1.100 pF at 5 mm to 1.958 pF at 15 mm which corresponds to a line slope of .086 pF/mm. Results from the line length test are shown in Figure 71. Increasing the line width also increased the capacitance, but only by 0.225 pF from the lengths 150 µm to 350 µm. The results also indicate that the capacitance will saturate as line width increases which is observed in the 0.180 pF

![Capacitor on glass, capacitance and phase vs. number of fingers](image)
change from 150 µm to 250 µm and much smaller 0.045 pF change from 250 µm to 350 µm. Results from varying line width are shown in Figure 72. It was also observed that increasing the number of fingers causes the capacitance to increase linearly with a slope of 0.171 pF/finger which is observable in Figure 73. The capacitors printed on Novele PET also exhibited no less than -88.80° phase which indicates these capacitors also have relatively low resistance compared to capacitance at 2 MHz.

Figure 70: Capacitor on Novele PET, capacitance and phase vs. gap size
Figure 71: Capacitor on Novele PET, capacitance and phase vs. line length

Figure 72: Capacitor on Novele PET, capacitance and phase vs. line width
4.2.3. Capacitors on Photopaper

The printed capacitors on photopaper were expected to have the smallest capacitance due to paper’s near-air dielectric constant, but it was discovered that this was an incorrect hypothesis. The largest capacitance achieved within the standard test procedure was 2.310 pF, higher than Novele PET but lower than glass. The reason for this greater-than-expected capacitance is because the immediate substrate for the capacitor is not paper but rather a coated PET substrate with paper as the underlying supportive material. The gap test also revealed that capacitance on photopaper is also less effected by the gap size at these dimensions; only a 0.192 pF difference was observed. Like glass and Novele PET, more significant capacitance changes may be seen with more significant gap changes. Results from this test are shown in Figure 74. The line length test also revealed the greatest capacitance change from 1.236 pF at 5 mm to 2.310 pF at 15 mm, and the slope of this line was 0.107 pF/mm. The results from this test are plotted in Figure 75. Increasing the line width displayed different results compared to glass and Novele PET substrates.
increased the capacitance linearly from 1.236 pF to 1.417 pF, and the slope of this line was 0.906 fF/μm which is plotted in Figure 76. The capacitance may saturate outside of these dimensions, but within the test parameters, the results are linear. Further testing of the capacitor outside of the standard test procedure is required. Finally, increasing the number of fingers also increases the capacitance with an exponential progression. The capacitance increased from 1.236 pF to 1.678 pF, and the results from increasing number of fingers is shown in Figure 77. Within the bounds of the capacitor test procedure, the interdigital capacitor on photopaper displayed different results compared to glass and Novele PET substrates. More detailed results may be achieved, but these tests were not within the scope of tests in this thesis.

Figure 74: Capacitor on photopaper, capacitance and phase vs. gap size
Figure 75: Capacitor on photopaper, capacitance and phase vs. line length

Figure 76: Capacitor on photopaper, capacitance and phase vs. line width
4.2.4. **Capacitor Repeatability**

The capacitor repeatability test was performed on Novele PET near the extents of the DMP-2830’s printing ability. The capacitor dimensions were as follows: width of 5 mm, line width of 50 µm, gap of 70 µm, and 3 fingers. The design was based on two parallel capacitors with the goal of implementing the design into a wax microfluidic sensor. Since the design was rather intricate and small, it was a true test of the printer’s capabilities as well as the repeatability. The results of this test are shown in Table 13, and it is observable from these results that the capacitor on Novele PET provided desirable results. The average capacitance of these capacitors was approximately 1.5017 pF, and the standard deviation was approximately 18.6 fF. These results show that the interdigital capacitor, even when printed at the lower extents of the dimensions printable by the DMP-2830, is reproducible and can be applicable in small-scale capacitive sensing devices.
<table>
<thead>
<tr>
<th>Gap</th>
<th>Length</th>
<th>Width</th>
<th>N</th>
<th>Capacitance</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>50</td>
<td>5</td>
<td>3</td>
<td>1.53E-12</td>
</tr>
<tr>
<td>70</td>
<td>50</td>
<td>5</td>
<td>3</td>
<td>1.52E-12</td>
</tr>
<tr>
<td>70</td>
<td>50</td>
<td>5</td>
<td>3</td>
<td>1.49E-12</td>
</tr>
<tr>
<td>70</td>
<td>50</td>
<td>5</td>
<td>3</td>
<td>1.52E-12</td>
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<tr>
<td>70</td>
<td>50</td>
<td>5</td>
<td>3</td>
<td>1.48E-12</td>
</tr>
<tr>
<td>70</td>
<td>50</td>
<td>5</td>
<td>3</td>
<td>1.50E-12</td>
</tr>
</tbody>
</table>

4.2.5. **Summary of Observations on Capacitors**

The methods used in these tests may be useful for the testing and device characterization of capacitors printed using various inks and substrates as well as different capacitor designs. The ability of glass, Novele PET, and photopaper to serve as substrates for capacitive devices is good overall with phase angles never falling below -88.8°. The repeatability test that was performed on capacitors, with notably small dimensions for the DMP-2830, provided an average capacitance of 1.5017 pF with standard deviation of 18.6 fF. For each substrate, it was observed that increasing the line length by 5 mm intervals had the greatest effect on the capacitance and, ultimately, achieved the greatest capacitance for the interdigital capacitor on each substrate. The substrate with the largest capacitance was glass with a capacitance of approximately 3.86 pF. The parameter that had the greatest slope for each substrate was the number of fingers in the capacitor design. Though increasing the number of fingers did not achieve the greatest capacitance in these tests, it can also significantly increase or decrease the capacitance due to the steepness of the slope. For the largest capacitances, the gap size should be minimized, and the finger width selected near the capacitance saturation point. Using this information, creative capacitors with parallel-plate architecture may be designed to serve various purposes in electronic devices.
4.3. **Inductors**

The design of the printed inductor was based on rectangular segments that, when organized, form a square planar inductor. Images of this inductor printed on Novele PET and photopaper are shown in Figure 78. This design was drawn using Illustrator as well as Matlab. Since there are numerous segments to the pattern with each segment having its own coordinates and dimensions, the Matlab program was designed with the purpose of providing the inductor designer the dimensions and coordinates of each segment. With both parameters, the pattern may be designed in Illustrator as well as the Pattern Editor. The user input to the program was inductor outer diameter (OD), number of turns, line width, and gap size. The program computed the coordinates and dimensions of each segment by using a generic model of a recognized pattern; the patterns are simply scaled replicas of each other. Another planar inductor design with rounded dimensions may be created by use of concentric circles, but this technique was not used due to the difficulty in accurately designing the desirable diameter, line width, and gap size.

![Planar inductor printed on Novele PET (left) and on photopaper (right)](image)

*Figure 78: Planar inductor printed on Novele PET (left) and on photopaper (right)*

The approach to fabricating planar inductor was different than the approaches to fabricating resistors and capacitors. Due to the amount of material required for printing the planar inductor, the strategy was modified to vary parameters, such as diameter, line width, and
gap size, to achieve the maximum inductance on one substrate, Novele PET. These maximizing parameters were then used to print inductors on glass and photopaper because, like capacitors, the maximizing parameters were expected to apply over all three substrates. Overall, this approach saved a significant amount of ink and substrate material, but the printing of inductors with the most effective dimensions was extremely difficult with low yield. Results will be discussed in the conclusion of this section. Since Novele PET has good printability with small drop sizes and high conductivity, it was the substrate of choice for optimizing the inductor structure. The prints for the tests were performed with 50% drop spacing and one layer on Novele PET. Once the maximizing parameters on Novele PET were obtained, inductors with the maximizing parameters were printed on photopaper and glass.

\[ Z_T \text{ and } \theta \text{ for each inductor recorded at 2 MHz using the Agilent E4980A Precision LCR meter, and the inductance } (L) \text{ and resistance } (R) \text{ were calculated with these parameters by using the equations } R = Z \times \cos(\theta) \text{ and } L = \frac{Z \times \sin(\theta)}{2 \times \pi \times f}. \]

The frequency setting was set at the highest possible on the LCR meter to increase the imaginary component of the complex impedance, and imaginary component of the complex impedance is proportional to the frequency and is represented by the equation \( Z_L = 2 \times \pi \times f \times L \). The phase angle of the inductor is described by the equation \( \theta = \tan^{-1}\left( \frac{Z_L}{R} \right) \). An observation was made that the trace resistivity has large effect on the phase angle of the printed planar inductor, and it was decided the resistance of the inductor was an important metric to calculate and record. Observations on the phase angle and resistance are discussed later in this section.

The first test conducted was to increase the gap size of an inductor with 25 mm OD, 200 \( \mu \)m line width, and 10 turns. A very small OD, small line width, and few turns were chosen to reduce the amount of ink used as well as reduce the substrate area consumed. The goal of this test was to observe an increase or decrease in inductance, not to maximize the inductance. It was observed that increasing the gap size from 200 \( \mu \)m to 800 \( \mu \)m decreased the phase from...
6.7° to 5.2°, therefore reducing the inductance. The results from this test are displayed in Figure 79 and Figure 80. From the inductance plot, Figure 80, it may be observed that the inductance was not significantly decreased (from 4.26 µH to 3.29 µH), and the inductance plot had a relatively linear trend with a slope of -0.0016 µH/µm. This test revealed that it is desirable to decrease the gap size to increase the phase angle. From this test, it may also be noted that the impedances of the inductors were extremely high due to the high resistances created by the thin line segments.

The second test performed was to increase the line width of an inductor with 25 mm OD, 200 µm gap, and 10 turns. Again, the small OD and few turns were chosen to minimize waste, but the gap size was purposely fixed at 200 µm to maximize the potential inductance of this inductor as shown in the gap test. It was observed that increasing the line width from 200 µm to 800 µm also increased the phase angle linearly from 6.7° to 19.1° with a slope of approximately 0.021 °/µm, but the inductance plot of these printed inductors shows non-linear results. In fact, the inductance decreases and then increases, as does the resistance plot. The resistance and inductance plots shown in Figure 82, and the phase and impedance plot is shown in Figure 81. The results of this test demonstrate that the line width should be larger to increase the phase angle of the inductor. Though this does not necessarily increase the inductance, it does improve the overall quality of the inductor by increasing the phase angle.

The third test performed on the inductor parameters was to increase the OD of the inductor from 25 mm to 45 mm. The gap size of this inductor was 200 µm, the line width was 800 µm, and the number of turns was 10. The small OD was maintained to, again, reduce waste. The gap size was minimized to the small dimension of 200 µm per the results of the gap test, and the line width was maximized to 800 µm per the results of the line test. The 45 mm maximum dimension was chosen due to the limiting 75 mm by 50 mm dimensions of the glass microscope slide. The impedance and phase plot for this test is shown in Figure 83. This test provided that increasing the OD of the inductor does not increase the phase by much,
approximately 2°, but it does linearly increase the inductance and the resistance of the inductor.

It was expected that the OD increase would increase the resistive component due to the forced increase in line length, but the increased inductance was a slight surprise since there was no prior knowledge that increasing diameter has this affect. The increase in inductance was from 1.98 μH to 4.99 μH with a slope of approximately 0.301 μH/mm. This feature served advantageously in the next test because it increased space for more turns while also increasing inductance. The inductance and resistance are plotted in Figure 84.

The final test performed was on an inductor with 800 μm line width, 200 μm gap size, and 45 mm OD. In this test, the number of turns was increased from 10 to 20. It was observed that increasing the number of turns in the inductor rapidly increased the inductance from 4.99 μH to 8.72 μH but caused it to saturate slightly at 9.85 μH. The saturation is likely due to the structure of the inductor and how the coils quickly converge on the center of the inductor. The impedance and phase plot is shown in Figure 85, and the inductance and resistance plot is shown in Figure 86. For more testing, the inductor could be printed on a larger substrate than a microscope slide which may reveal the effect of increasing number of turns while not converging directly on the center of the inductor. The results from this test provided that an increase in the turns on an inductor would increase the inductance as well as the resistance. Figure 79
Figure 79: Inductor on Novele PET, impedance and phase vs. gap size

Figure 80: Inductor on Novele PET, resistance and inductance vs. gap size
Figure 81: Inductor on Novele PET, impedance and phase vs. line width

Figure 82: Inductor on Novele PET, resistance and inductance vs. line width
Figure 83: Inductor on Novele PET, impedance and phase vs. OD

Figure 84: Inductor on Novele PET, resistance and inductance vs. OD
From the above tests, the maximizing parameters were extracted: gap size of 200 µm, line width of 800 µm, turns count of 20, and OD of 45 mm. Inductors were then printed on glass in one layer at drop overlap of 50% and on photopaper in two layers at 50% overlap. These
parameters produced 0.059 Ω/sq and 0.050 Ω/sq for photopaper and glass respectively whose resistivities are close to the 0.077 Ω/sq sheet resistance of Novele PET when printed in one layer at 50% drop overlap. Note that the drop overlaps and number of layers on photopaper and Novele PET are not the optimal drop overlaps that correspond to the least sheet resistance. The reason these parameters were set like this was to reduce the amount of ink required to print the planar inductor and provide comparable results to the inductor printed on Novele PET. For a repeatability test, three smaller planar inductors of 25 mm OD, 800 μm line width, and 200 μm drop spacing were printed on photopaper using the optimal printing parameters: 3 layers at 50% drop overlap for approximately 0.045 Ω/sq sheet resistivity. Photopaper was used for this test because it provided the most desirable phase angle compared to glass and Novele PET.

Before presenting the results, it should be established that an inductance of 9.378 μH was calculated using the Modified Wheeler Equation available in [122] [123]. This value served as a reference for the measured inductance values. The phase angle of an ideal inductor is 90°, but the printed planar inductor contains such high resistance that, at 2 MHz, it is far from 90°. Table 14 displays the results from printing inductors on Novele PET, photopaper, and glass. The measurements were again taken at 2 MHz to maximize the phase angle.

The inductors printed on photopaper and Novele PET both produced inductances that exceed the Wheeler approximation by nearly 0.5 μH. The cause for this is likely due to the droplets overwhelming the designed trace dimensions causing the gap to decrease slightly. This effect is described in more detail in 3.1 Pattern Design. Further testing of this effect on the inductance may be conducted but is not within the scope of this thesis.

The inductor printed on glass was extremely difficult to print and, therefore, difficult to obtain any results for. Of five attempts to print the inductor on glass at the optimal dimensions, only one successful print of an inductor was achieved, and an inductance of 6.118 μH was measured. Causes for this difficulty were likely due to the difference in ink and substrate used to
fabricate the inductor on glass compared to Novele PET and photopaper. Figure 87 displays an image taken through the sight of a stereoscope showing stray droplets forming during the printing of 200 µm width vertical lines. There are a few conclusions that may be drawn from these results. The stray droplets were likely caused by a single fowl-jetting nozzle which is not an uncommon occurrence with the DMP-2830 nozzles. Mitigating this issue is made simple by selecting a range of nozzles that jet properly. Another conclusion is that the stray droplets occur only in one consistent section which may be an indication that a nozzle was blocked and needed cleaning. The cleaning cycles may be changed to become more frequent with the intent of preventing the blockage of nozzles, and these settings are specific to each ink and cartridge. These statements are hypotheses that may be tested to solve the problem of poor printing results. Future work may include the modification of the cleaning cycles, jet-settings, as well as waveform settings to obtain the best results for printing on glass. Since greater interest is placed on flexible platforms within this thesis, the inductor on glass was not pursued further.
Figure 87: Stereoscope image of printing error during inductor printing on glass

Table 14: Inductors printed on glass, Novele PET, and photopaper

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Impedance (Ω)</th>
<th>Phase (°)</th>
<th>Inductance (H)</th>
<th>Resistance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photopaper</td>
<td>176.51</td>
<td>44.71</td>
<td>9.8808E-06</td>
<td>125.45</td>
</tr>
<tr>
<td>Glass</td>
<td>159.84</td>
<td>28.75</td>
<td>6.1184E-06</td>
<td>140.14</td>
</tr>
<tr>
<td>Novele PET</td>
<td>271.01</td>
<td>27.17</td>
<td>9.8493E-06</td>
<td>241.10</td>
</tr>
</tbody>
</table>

For comparison purposes, three more inductors were printed within the repeatability test. As mentioned previously, the repeatability test was designed to test an inductor printed with the least sheet resistance on photopaper: 50% drop overlap with three printed layers leading to sheet resistance of 0.045 Ω/sq. Since inductors require a significant amount of ink and substrate to print, lower quality devices with fewer layers and lesser drop overlaps were printed which leads to higher parasitic resistance in the inductor turns. The second test within the repeatability test was designed to test the reliability of the sheet resistivity test as well as approximate the
best-case inductance based on the low-quality (high parasitic resistance) test devices. The test was performed with 25 mm OD, 800 µm line width, 200 µm gap inductor designs with one inductor type printed at 50% drop overlap with two layers, and the other inductor type printed at 50% drop overlap with three layers which are the most ideal parameters for low sheet resistance. Results for the inductors printed in two layers are shown in Table 15. The two-layer inductors provided an average inductance of 2.0264 µH with standard deviation of 0.1514 nH and average phase of 31.60° with standard deviation of 0.04°. From these results the best-case phase angle was calculated: 41.63°. The three-layer inductors were then printed to compare the estimated best-case to the measured best-case. Results for the inductors printed in three layers are shown in Table 16. The 3-layer inductors provided an average inductance of 2.0264 µH with standard deviation of 1.95 nH and average phase of 40.90° with standard deviation of 0.04°. Comparing the results, it was observed that the measured best-case phase angle was within 1.75% of the calculated best-case phase angle. The inductance of each pattern also remained the same which was expected.

Table 15: 2-layer inductor repeatability test

<table>
<thead>
<tr>
<th>Inductor on Photopaper, OD=25mm, Turns=10, Line Width=500um, Gap=200um</th>
<th>Impedance</th>
<th>Phase</th>
<th>Inductance</th>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>48.67</td>
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<tr>
<td></td>
<td>48.55</td>
<td>31.63</td>
<td>2.0262E-06</td>
<td>41.34</td>
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<tr>
<td></td>
<td>48.55</td>
<td>31.64</td>
<td>2.0266E-06</td>
<td>41.34</td>
</tr>
</tbody>
</table>

Table 16: 3-layer inductor repeatability

<table>
<thead>
<tr>
<th>Inductor on Photopaper, OD=25mm, Turns=10, Line Width=500um, Gap=200um</th>
<th>Impedance</th>
<th>Phase</th>
<th>Inductance</th>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>38.96</td>
<td>40.86</td>
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<td>38.84</td>
<td>40.90</td>
<td>2.02373E-06</td>
<td>29.35</td>
</tr>
</tbody>
</table>
4.3.1. Summary of Observations on Inductors

The planar inductor proved to be the most challenging passive device to print due to the amount of material required to print the patterns as well as the large-area and close-proximity of the small dimensions within the planar inductor design. Print defects were most prevalent in that of glass with only one in five attempts successful. Novele PET had desirable print properties and satisfactory results but did not provide the best device characteristics. The best device performance was obtained by printing three layers at 50% drop overlap of JS-B25HV ink on the photopaper substrate of the 45 mm OD, 200 µm gap, and 800 µm line with planar inductor design. This pattern provided an inductance of approximately 9.8808 µH and phase angle of 44.71° at 2 MHz. An experiment was conducted to test the validity of the sheet resistance and its final effect on the phase angle. Two-layer and three-layer inductors were printed at 50% drop overlap. The two-layer inductor provided average inductance of 2.0264 µH and average phase angle of 31.60°. Using this data, the best-case phase and inductance were calculated as 41.63° and 2.0264 µH. The three-layer inductor was printed which provided an average inductance of 2.0264 µH and average phase angle of 40.90°. Printing the three-layer inductor proved that the sheet resistivities were valid values causing the parasitic resistance to decrease the phase angle to within 1.75% of the calculated value. The final effect of the sheet resistance on the phase angle was that the decrease in sheet resistance significantly decreased the parasitic resistance, therefore, increasing the phase angle while maintaining near-identical inductance values. This is a desirable characteristic, but due to the defects caused by printing greater than three layers, such as ink overflow, increasing layers cannot be performed indefinitely.

The largest obtained phase angle was observed from the 45 mm diameter, 800 µm line width, 200 µm gap inductor, and was approximately 44.71° for an inductor printed with two layers. If this inductor was printed with three layers, the best-case phase angle would be 55.03° which remained a non-ideal inductor. The conclusion made was that the inkjet-printed inductor is not an ideal inductor device by any means, but, since the phase of an inductor is a function of
the frequency, the phase angle may be significantly increased by increasing the operating frequency from 2 MHz to hundreds of MHz to even GHz frequencies. In fact, increasing the operating frequency of the device to the near-field-communication frequency (NFC) band (13.56 MHz) would increase the phase angle to 84.10°. This is still undesirable, but the mere fact that 6 times frequency increase has such great effect on the inkjet-printed planar inductor makes a promising argument for this device. Further investigations may be pursued by greater modification of the geometry of the planar inductor.
CHAPTER 5: APPLICATIONS

5.1. **Bend Sensor**

The bend sensor was a meander-type, resistive sensor fabricated on the Novele PET substrate using JS-B25HV Ag NP ink. This sensor has useful application in scenarios where fully-flexible, cheap strain/deflection-type measurements are to be made. In other applications, this sensor may detect angular and linear motion changes as well as end points. For a sensor that required cheap circuitry and basic components to implement, the resistive bend sensor required large resistive changers per bend unit input. A larger resistive change provided for greater voltage drops in a voltage sensing circuit, thus creating a system easy to implement without expensive nanovolt-sensing circuitry. It was observed that printing a meander resistor with many legs and thin line width produced a resistor with the greatest resistive variation per bend unit. The resistor with these results was a meander resistor at 40 mm length with eight legs at 150 µm line width. These results were obtained by printing four meander resistors with varying line width and number of legs. The slope of each line was calculated in Microsoft Excel which provided the change in resistance per bend unit in units of ohms/caliper-mm (ohms per caliper-millimeter). To induce a bend onto the bend resistor, a test jig, shown in Figure 88 was assembled to precisely control the bending of the sensor in millimeters using a dial caliper. The bend sensor in Figure 88 is shown being bent in the outward direction which increases the resistance of the meander resistor. The photos display the bending of the sensor in 0%, 50%, and 100% bend where 0% bend is at 0 mm, and 100% bend is at 17 mm.
The bend sensor was printed at 40% drop overlap on Novele PET and thermally sintered in the vacuum oven for 25 minutes at 85 °C. Two of each of the four resistors were printed to assess the repeatability of resistance as well as bending slope. The first resistor printed was a 40 mm length meander resistor with 250 µm line width and two legs. The second resistor printed was a 40 mm length meander resistor with 350 µm line width and two legs. The third resistor printed was, again, a 40 mm length meander resistor with 150 µm line width but with four legs. Finally, the 40 mm length meander resistor with 150 µm line width and eight legs was printed.

Figure 89 displays an example of the slope calculations for the 40 mm bend sensor with 250 µm line width and two legs. A negative caliper amount indicates the bending sensor bending in the inward direction, and a positive caliper amount indicates the bending sensor bending in the outward direction. As seen in Figure 89, the slope of the inward bend of this sensor was approximately 0.0846 Ω/mm, and the slope of the outward bend was approximately 0.0543 Ω/mm. Table 17 displays the results from the bending
tests of each fabricated resistor. The final considered value was the average bending slope, indicated by the “Avg. Bend” column in the table, which dictated the meander resistor design with greatest resistance change per millimeter of bend using the caliper. It can be observed that the 4-leg bending resistor and the 8-leg bending resistor produced the largest slopes with the largest of the 8-leg sensor being 0.28885 Ω/mm. Three of these bending sensors were printed, and the standard deviation and average resistance values at rest are in order as follows: 10.874 Ω and 531.393 Ω for outward bend, 10.511 Ω and 532.447 Ω inward bend.

On top of the results presented above, another curious observation on the bend sensor plots was made and is shown within Figure 89. Circled in red is a small region, directly off the zero-bend mark, where bending of the sensor displays much higher slope than the rest of the bend amounts. This region of operation may have application in sensing very small bends induced on the sensor. The investigation of this function may be performed in future work by utilizing a more precise test jig that utilizes a piezoelectric actuator or stepper motor.

Figure 89: Plot showing the bending resistance of a sensor with respect to the caliper amount
Table 17: Bend sensor design slopes

<table>
<thead>
<tr>
<th>Line Width (µm)</th>
<th>Legs</th>
<th>Resting Outward</th>
<th>Resting Inward</th>
<th>Slope Outward</th>
<th>Slope Inward</th>
<th>Avg. Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>2</td>
<td>138.95</td>
<td>138.55</td>
<td>0.0543</td>
<td>0.0846</td>
<td>0.06945</td>
</tr>
<tr>
<td>250</td>
<td>2</td>
<td>141</td>
<td>140.94</td>
<td>0.0564</td>
<td>0.1064</td>
<td>0.0814</td>
</tr>
<tr>
<td>350</td>
<td>2</td>
<td>95.73</td>
<td>95.26</td>
<td>0.0359</td>
<td>0.0567</td>
<td>0.0463</td>
</tr>
<tr>
<td>350</td>
<td>2</td>
<td>97.11</td>
<td>96.57</td>
<td>0.0481</td>
<td>0.0565</td>
<td>0.0523</td>
</tr>
<tr>
<td>150</td>
<td>4</td>
<td>386.69</td>
<td>386</td>
<td>0.1948</td>
<td>0.2357</td>
<td>0.21525</td>
</tr>
<tr>
<td>150</td>
<td>4</td>
<td>397.67</td>
<td>395.85</td>
<td>0.2787</td>
<td>0.2424</td>
<td>0.26055</td>
</tr>
<tr>
<td>150</td>
<td>8</td>
<td>533.21</td>
<td>537.21</td>
<td>0.2038</td>
<td>0.3739</td>
<td>0.28885</td>
</tr>
<tr>
<td>150</td>
<td>8</td>
<td>543.71</td>
<td>42.26</td>
<td>0.2661</td>
<td>0.2266</td>
<td>0.24635</td>
</tr>
<tr>
<td>150</td>
<td>8</td>
<td>517.26</td>
<td>517.87</td>
<td>0.2691</td>
<td>0.2184</td>
<td>0.24375</td>
</tr>
</tbody>
</table>

Upon concluding that the 40mm length, 150 µm line width, 8-leg meander resistor was the most suitable of these resistors to implement into a circuit, further testing was performed with the objective of turning millivolt changes across the bend sensor into voltages easily distinguishable by a microcontroller. The design of the bend sensor circuit was based on the Arduino Uno which has a 10-bit, 5 V analog-to-digital converter (ADC) as well as a 5 V DC supply for peripherals. Ten-bit resolution provides for $2^{10}$ resolution: 1023 steps within the 5 V range of the microcontroller. For reading of sensor values in a 0-5 V scale, a differential amplifier was implemented using an LM-741 operational amplifier. The differential amplifier circuit consisted of a 100 Ω sense resistor and multiple trim pots for tuning of the reference voltage and gain. For this test, the bend sensor chosen to implement in circuitry was the sensor with average slope of 0.2435 Ω/mm. For simulation purposes, the results from the bending test were used to approximate amplifier output values based on a gain of 250. The purpose of this experiment was to demonstrate the practical operation of the bend sensor in circuit form which is why the Arduino Uno was not implemented into the circuit.

The differential amplifier was designed to strip away 0.82 V from the voltage of the sense resistor. Since the voltage sense is across the 100 Ω resistor, a larger voltage drop occurs across the bend sensor when larger resistance is created from outward bending causing...
a reduction in voltage across the sense resistor. Conversely, a smaller voltage drop will occur across the bend sensor when smaller resistance is created from inward bending causing an increase in the voltage across the sense resistor. For this reason, the baseline “strip-off voltage” was set at the maximum inward bend of the sensor where the resistance is the least and the voltage drop across the sense resistor is the greatest. At 17 mm of inward bend, the voltage across the sense resistor was calculated to be 0.8159 V, thus a good starting strip-off (Vref) voltage was set at 0.82 V. The strip-off voltage may be tuned using a trim pot on the circuit board which is indicated by Rref on the circuit schematic shown in Figure 91. Shown in Figure 90 are the measured resistance values versus the caliper bend amount as well as the simulated voltage output of the differential amplifier. Note that the resistances at zero bend are not equal indicating that the resistor did not return to the original resistance state. The variation between outward and inward bending resting states was approximately 0.61 Ω. This value would be zero in an ideal bend sensor. The calculated values for resistive components in Figure 91 were as follows: $R_1 = R_2 = 584 \, \Omega$, $R_3 = R_4 = 146 \, \Omega$, $R_5 = 5 \, k\Omega$, $R_{\text{sns}} = 100 \, \Omega$. 
Figure 90: Plotted data and simulated voltage from bend sensor measurements

Figure 91: Circuit of the differential amplifier
The bend sensor circuit was tested using the Tektronix TBS1102B-EDU Digital Oscilloscope, Agilent E3630A Triple Output DC Power Supply, and the Hewlett Packard E3633A DC Power Supply. An image of the circuit is shown in Figure 92, and the oscilloscope reading is shown in Figure 93. As observed on the oscilloscope output, the resting state voltage across the sense resistor (blue channel 2) was approximately 824 mV, and the resting state of the voltage output of the differential amplifier (yellow channel 1) was approximately 2.64 V. Compared to the simulated voltage results, the measured reference voltage was off by approximately 5 mV. \( R_{\text{ref}} \) was tuned using the trim pot to achieve \( V_{\text{ref}} = 835 \) mV. It was also observed that the resting state of the bend sensor did not immediately return to the original resting state which resembled the measured resistance results in Figure 90. After 15 seconds, sometimes less, the plastic sensor would return to the resting output voltage of 2.64 V. Due to the hookup fashion of the bend sensor on the breadboard, the maximum and minimum voltages were not measured.

Figure 92: Bend sensor differential amplifier circuit
5.1.1. **Summary of Observations on the Bend Sensor**

The fabricated bend sensor was demonstrated as a practical device by utilizing the functionality of a simple differential amplifier circuit. The resistance of the chosen bending sensor for testing was between $512.81 \, \Omega$ (17 mm bend inward) and $522.65 \, \Omega$ (17 mm bend outward). The output of the differential amplifier sensor circuit was oriented around a 0-5 V voltage input of an Arduino Uno microcontroller, where the resting state voltage was centered at 2.64 V. These results were obtained by stripping off approximately 835 mV of sensed voltage and applying a voltage gain of 47.96 db. It was also observed that the amplifier output voltage returned to its original resting voltage state of 2.64 V even after 10 rigorous bends of the sensor.

5.2. **Sensor on Wax/Paper**

Microfluidic devices are currently being developed at the electronics fabrication labs at Ohio University. Devices of interest include, but are not limited to, paper-based wax microfluidics which are currently being explored by another MS candidate, Tianyi Cai. The fabrication techniques of interest mainly comprise of printing techniques; printing microfluidic...
devices demonstrates the complementary nature of simple, low-power fabrication and the ability to create a variety of printed electronics. In this thesis, a novel capacitive sensing device was fabricated on Novacentrix Novele PET which utilized a wax microfluidic channel printed on chromatography paper as the fluid transport medium. The final sensing device was capable of sensing four concentrations of isopropyl alcohol (IPA) in deionized (DI) water as well as measuring the flow rate of fluid through the microfluidic channel. The sensor design was fabricated strictly by using printing devices and thermal processing equipment. The device described in this thesis was simple and in an infant state but has potential to lead to more advanced electrochemical sensing designs which are being pursued by T. Cai. In this section, the device design, fabrication process, and results are discussed.

As mentioned previously, the substrates utilized to fabricate the capacitive wax microfluidic sensor were Novacentrix Novele PET and Whatman Chromatography Paper. The inks used were JS-B25HV Ag NP ink and Xerox brand black color wax ink, the standard ink for the wax printer. Two printing machines were used to fabricate this device: the Fujifilm DMP-2830 for printing of Ag NP ink and the Xerox ColorQube 8570 for printing of wax patterns.

The microfluidic wax channel was designed using Illustrator and was saved as a PDF file for printing on standard letter-size paper using the ColorQube printer. The channel pattern dimensions were as follows: 1 mm channel width, 25 mm channel length, and 5 mm diameter drop deposit areas all contained within a 37 mm by 10 mm black rectangle. The capacitive sensing element was also designed using Illustrator but was saved as a bitmap file and converted to a printable file using the Image to File Converter in the Drop Manager. The pattern contained two interdigital capacitors in parallel spaced 5 mm apart with 2 mm length, 50 µm width fingers, and 70 µm gap. This design was selected to measure capacitance of two capacitors while only having a single-channel measurement device. Figure 94 displays screenshots of the wax channel and capacitor patterns.
The novelty of the capacitive wax microfluidic sensor was within the process and procedure established to fabricate the sensor. Since printing the capacitive sensing device on chromatography paper produced sub-optimal and easy-to-deform capacitors, the paper wax channel and capacitive element were printed separately; the capacitive sensor was much more reliable when printed on PET film. Operation of the sensor required the capacitive sensing element to be in direct contact with the fluid of interest, and, to satisfy this need, the wax utilized to print the fluidic channels served dual purpose as fluidic channel and bonding agent to mount the fluidic channel onto the capacitive element. This method promoted sensor fabrication without the introduction of additional hydrophobic bonding materials and may be applied with other types of more chemically neutral wax inks. The wax also created a barrier to prevent leeching of fluid from the fluidic channel. Bonding the Novele PET and chromatography paper was the final step in the fabrication process, and, prior to bonding, fabrication processes were performed on the individual substrates.

The first step in fabricating the wax microfluidic sensor was to print the capacitive element on Novele PET using Ag NP ink. The pattern was printed at 50% drop overlap and thermally sintered in a vacuum oven for 25 minutes at 85 °C under a 25 mL Hg vacuum. The patterns were then cut into individual pieces and fastened, using Scotch tape, face-up to a sheet of paper with a printed “guide pattern” that indicated the location of fluidic channel print. Using the ColorQube printer, three layers of the fluidic channel were printed on Novele PET with 5
second, 120 °C thermal heating cycles on a hot plate between layers one, two, and three; the final layer was not heated. The wax channel on Novele PET maintained the 1 mm channel width even after each heating cycle. Layers were printed by re-feeding the paper into the printer, and an image of a single wax layer printed on the capacitor pattern is shown in Figure 95.

Figure 95: Single layer of wax channel printed on Novele PET

The second step in the process was to fabricate the wax microfluidic channel on the chromatography paper. 38 mm strips of the chromatography paper were cut using a paper cutter and fastened, again using Scotch tape, to a sheet of paper with a different guide pattern than the capacitor sheet. Four layers of wax ink were printed on the chromatography paper with 120 °C thermal heating cycles on a hot plate between layers one, two, and three. Heating was performed until the wax ink fully soaked into the paper without sealing the channel: approximately 15 seconds per layer. Layers three and four were not heated. After thermal processing of layers one and two, the wax channel decreased in size from 1 mm to approximately 500 µm.

The final step in the process was the bonding process. The hot plate was reduced to a lower temperature, 90 °C, to prevent the wax ink printed on Novele PET from leeching into the
chromatography paper. The Novele PET and chromatography paper channels were aligned with the shiny sides of wax ink facing each other and taped together with one piece of tape while avoiding taping of the channel or wax pattern. The pattern was set on the hot plate and pressed firmly using a semi-rigid piece of plastic (ie. credit card) for 6 seconds. Another method that produced good results was to “squeegee” the semi-rigid piece of plastic along the wax channel slowly, taking approximately 10 seconds to squeegee the full length of the wax pattern. The second method was not preferred because the sample was difficult to hold steadily in place while the squeegee movement was performed. After the bonding process was performed, excess paper and plastic material was trimmed away for aesthetic purposes. A previously used microfluidic device is shown in Figure 96.

Figure 96: Fully fabricated wax microfluidic sensor front (left) and back (right)

The microfluidic sensor was tested at 2 MHz using the E4980A LCR meter. The sweep function was utilized, and the settings were as follows: step sweep, trigger delay of 250 ms, and medium measurement time. Four concentrations of IPA by mass in DI water were tested: 0%, 4.9%, 9.3%, and 20% IPA. Three samples of each concentration were taken, all using a new, unused, sensing device. Using a pipette, a single droplet of solution was applied to the circular
pad closest to the capacitive element; at this time, the sweep was started. The results of each concentration were averaged, and the averages were plotted and are shown in Figure 97. As observed in the plot, each concentration of IPA displayed consistently varying results.

There are two noticeable spikes in capacitance for each solution. The first rise occurs when the solution reaches the first capacitor, and the second rise occurs when the solution reaches the second capacitor. The time between these rises may be used to indicate the flow rate of fluid through the channel. Within these samples, DI water had the quickest flow rate of approximately 769 µm/s, and 20% IPA solution had the slowest flow rate of approximately 0.263 µm/s. It may also be observed from the plot that locating the second rise in capacitance becomes significantly more difficult as the concentration of IPA increases indicating that smaller concentrations of IPA may be more reasonable solutions for a capacitive device with this design.

As IPA concentration increased, the capacitance was expected to decrease due to the decrease in overall permittivity of the solution. The relative permittivity of DI water is approximately 80, and the relative permittivity of IPA is approximately 17.9, therefore, higher IPA content should lead to lower permittivity. As observed in Figure 97, the final resting capacitance of DI water was 9.65 pF, and the final resting state of the 20% IPA solution was 6.41 pF. As IPA concentration increased, the capacitance decreased which confirms the expected results. Solutions of higher IPA concentration decreased the permittivity which caused the capacitance to decrease.

Other applications of this device include a novel, low-cost and high-performance viscometer. A known fluid and an unknown fluid may be compared to distinguish between different fluids in simple, paper-based test elements. These devices may be valuable in field studies to pre-screen fluid samples.
5.2.1. **Summary of Observations on the Microfluidic Sensor**

A novel design of a capacitive wax microfluidic sensor was used to sense different concentrations of IPA in DI water. A parallel-connected interdigital capacitor was used as the sensing element, and a wax channel printed on chromatography paper was used as the microfluidic channel. The two materials were bonded using the printed wax which promoted sensor fabrication without the necessity for adhesive materials. Four concentrations of IPA by mass in DI water were tested: 0%, 4.9%, 9.3%, and 20% IPA. For each of the four solutions, three unused devices were tested, and the results were averaged. The averaged results provided that increasing IPA concentration decreased flow rates as well as decreased capacitance. The flow rate of DI water was quickest at approximately 769 µm/s, and the 20% IPA solution was the slowest of approximately 0.263 µm/s. The final capacitance with DI water was highest at 9.65 pF, and the final capacitance with the 20% IPA solution was lowest at 6.41 pF.

![Wax Microfluidic Capacitance vs. Time](image)

**Figure 97: Average capacitance for 0% to 20% solutions of IPA/DI water**
The fabrication technique introduced in this thesis brought together the best of two worlds (printed sensor on PET substrate and solution-wicking paper channel). Hence, many other, and more complex, devices can be fabricated utilizing this approach. For example, this device has potential to be used in electrochemical sensing applications where an analyte may be placed between the first and second capacitor. Upon reacting with the analyte and contacting the second capacitor, solutions may be examined before and after reaction to determine more specific chemical content.


CHAPTER 6: CONCLUSION

In this thesis, optimization of the Fujifilm Dimatix DMP-2830 for fabrication electronic devices was performed. Two Ag NP inks on glass, Novele PET, and photopaper were characterized by printing VDP patterns to assess the effect of modifying printing parameters such as drop overlap, oven time, and number of layers on the sheet resistance. Resistors, capacitors, and inductors were also printed and characterized in detail. Geometric parameters of the patterns, such as line width, gap size, turns, and fingers, were varied to weigh their effect on the resistance, capacitance, and inductance of the components. Two sensors, bend sensor and microfluidic sensor, were also fabricated to demonstrate the practicality of utilizing printing technology to fabricate devices.

The VDP pattern assisted in optimizing the printing of Ag NP inks on glass, Novele PET, and photopaper. It was observed that increasing the number of printed layers was the most effective at decreasing the sheet resistance. JS-B40G, an ink specially designed for glass and uncoated polymers, reached a low sheet resistance of 0.054 Ω/sq when printing four layers at 20% drop overlap. JS-B25HV, an ink specially designed for coated substrates, reached a low sheet resistance of 0.041 Ω/sq on photopaper when printing 3 layers at 50% drop overlap and a low sheet resistance of 0.054 Ω/sq when printing 3 layers at 30% drop overlap. It was also observed that increasing oven time and increasing resolution decreased the sheet resistance but had less significant of an impact compared to increasing number of printed layers.

The resistors printed on each substrate were characterized by using three resistive structures: straight-line, zig-zag, and meander. Increasing line length linearly increased resistance for each pattern and increasing line width decreased resistance rapidly. The slope for each linear curve was calculated and may be used to design resistors. For example, the slope of a meander resistor on Novele PET was 8.223 Ω/mm. This value may be used to design resistors with specific values by simply varying the length. Resistive patterns in the range of 4 Ω to 230 Ω were printed within the standard test procedure established for resistors in this thesis.
The straight-line resistors produced the smallest resistances while the zig-zag and meander resistors were designed to increase the resistance drastically. Meander and zig-zag resistive designs may also be printed to reduce the area required per component. The resistor has potential in sensing application; in this thesis, the resistor served as a bend sensing device.

The capacitor structure of choice in this thesis was the interdigital capacitor. Printing planar capacitors provided relatively tiny capacitances, specifically, in the pF range. The largest capacitors printed per substrate within the standard test procedure established for capacitors were as follows: glass at 3.86 pF, photopaper at 1.96 pF, and Novele PET at 2.31 pF. Line length, gap size, finger width, and number of fingers were all varied to achieve the greatest possible capacitance. The greatest capacitances were achieved by increasing the line length by intervals of 5 mm followed closely by increasing the number of fingers. The slopes for the linear characteristics were also calculated and may be used to design capacitors with specific capacitances. For example, the slope of increasing line length of a 150 µm gap, 150 µm line width capacitor from 5 mm to 15 mm on photopaper was 0.107 pF/mm. The interdigital capacitor was also used for sensing devices in this thesis in which a more creative capacitor design was utilized. For applications that require much larger capacitors, standard parallel-plate capacitors may be designed by reversing the pattern and printing on double-sided substrates.

The square-planar spiral inductor was also printed on glass, and parameters such as line width, outer diameter, and gap size were varied. To reduce waste and material use, Novele PET was the substrate used to optimize the planar inductor due to its desirable printing characteristics. The inductors were measured with the LCR meter at 2 MHz to achieve the greatest possible phase angle. Upon experimenting with varying parameters, the optimal inductor performance was reached when line width increased, gap size decreased, and outer diameter increased; these were the maximizing parameters established using the Novele PET substrate. Inductors with the maximizing parameters were then printed on glass and photopaper. The best performing inductors were those printed on photopaper; the low parasitic
resistance of printing two layers led to the greatest obtained phase angle of 44.71° and
inductance of 9.88 µH. The inkjet printed inductor was the most difficult device to print due to
the large number of defects presented when printing on glass. Of five trials only one successful
inductive device was printed, and it was determined that glass required more research for
optimization. Though the square-planar inductor printed on photopaper provided the highest
phase angle of 44.71°, the maximum possible phase angle within the standard test procedure
would be 55.03° or less. To increase the phase angle of the inductor, the operating frequency
should be increased. For example, near-field-communication is performed at 13.56 MHz which
can increase the phase angle to possible 84.11°. It was apparent that the square-planar
inductor was not a good inductor due to the extremely high parasitic resistance of the coils. To
mitigate the high parasitic resistance, higher conductivity inks not present within this thesis may
need to be explored.

Two sensors were also fabricated strictly with printing technology. The first sensor was a
bend sensor based on the meander resistor structure. The sensor had a resting resistance of
517 Ω and varied in resistance +/- 5 ohms when bent using a caliper. To display the practicality
of such device, a differential amplifier circuit was designed around an Arduino Uno with a 0-5 V
ADC and the resting voltage was set at approximately 2.64 V. The second sensor was a novel
capacitive wax microfluidic sensor that was used to sense flow rate as well as sense four
concentrations of IPA in DI water. A unique parallel-connected capacitor design was
implemented for measurement with a single-channel device.

The research performed in this thesis does not envelope the full potential of inkjet
printing technology. Instead, it was performed to establish a starting place when exploring new
inks, substrates, or devices. Since the DMP-2830 is a new system to the electronics fabrication
labs at Ohio University, this thesis may also serve as a training tool for students entering inkjet
fabrication research.
6.1. Challenges

There were few but prominent challenges whilst printing with the DMP-2830. The most prevalent challenge that had to be overcome was the selection of the best-jetting nozzles. Printing performance relied heavily on consistent jetting of all nozzles to be used. Nozzles may be examined by using the Drop Watcher. Here, cleaning cycles may be performed, jet settings may be adjusted and viewed, and nozzles troubleshooted. It was observed that visual confirmation of the jetting of nozzles in the Drop Watcher screen does not guarantee that nozzles will function consistently when pattern printing. Figure 98 displays screenshots from the fiducial camera of the effect of malfunctioned nozzles. Commonly, when nozzles were not jetting or jetting intermittently, stray blank lines will appear as shown in the left-most image. Another scenario was when nozzles jet off center as shown in the right-most image. The most effective method in preventing these occurrences was to select the range of nozzles that produced the best results. This was done by trial and error printing a test pattern and using the fiducial camera to assess the quality. Cleaning was also performed at times when less than five nozzles were operational. Cleaning consisted of placing the cartridge on top of a glass slide and dropping a small amount of water in the nozzle area. The inks used were water-soluble which allowed water as the cleaning agent. The cartridge was soaked for 5 minutes or less in the water, dried with light compressed air, and tested again.
The best print results were obtained directly after filling a cartridge with fresh ink. Since the DMP-2830 was used to print multiple devices, cartridges were required to be in service for several days and even weeks. Degradation of print quality was observed over time due to malfunctioning nozzles, and, at this time, new cartridges were required to achieve optimal printing performance.

6.2. Future Work

The use of inkjet printing devices for the fabrication of electronics has been around for quite some time, but there is still potential for novel designs and consumer application. Of the passive devices studied in this thesis, the inductor has the most potential for future work due to the high probability of printing issues on glass as well as the large parasitic resistance introduced with the printed windings. For device improvement, modifying inductor geometry, selecting new inductor designs, and utilizing new inks and substrates may allow the fabrication of a high-performance printed inductor.

Another device with potential for future work within this thesis is also the bending sensor. As mentioned within the device’s respective section, there is a region of operation where the bend sensor displays significantly higher bending slope (from 0 mm bend to 1 mm bend) relative
to the rest of the bending range (from 1 mm bend to 17 mm bend). This region may serve in applications where less-than-one-millimeter bend sensing is required. This small operating region may be further investigated using a more reliable test jig.

The capacitive wax microfluidic sensor also has much future work ahead. The demonstration of the device sensing various concentrations of IPA confirmed that there are practical applications for capacitive wax microfluidic sensors. Further research can be performed utilizing electrochemistry to be selective in measuring material concentrations. Applications for this device are extremely broad, but the application that may have greatest value is sensing of contaminants in water. Devices sensitive to heavy metals or agriculture chemicals may be useful in quick diagnosis of water quality in regions where clean water is inaccessible, expensive, or polluted.
REFERENCES


