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State University
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Electrical Engineering Department

Senior Project

Inkjet Printed Transistor

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Abstract

Wearable sensors currently use off-the-shelf integrated circuits for signal amplification. These fabricated ICs have packages that make attaching them to a wearable substrate difficult; current integrated circuits would be too bulky for most uses in wearable technology and the silicone is not at all flexible. The current integrated circuits also have a slow turnaround time and are typically much more expensive to fabricate. Wearable substrate-based printed transistors (like an adhesive band-aid patch) eliminate the need to use fabricated amplifier ICs. This project's end goal is to print and characterize transistors on a wearable substrate and use them to build a simple amplification circuit to reduce cost and manufacturing time associated with wearable sensor fabrication. Over existing manufacturing techniques inkjet fabrication would allows for faster and lower cost changes to transistor designs and reduces the cost of very small production run integrated electronics by avoiding the expensive photolithography process used today. In addition, the inkjet process could open the door to more sustainable and biodegradable materials to be used in electronics. Our attempts at creating an usable inkjet based transistor were not successful. We ran into significant problems with the choice of dielectric; the original dielectric that we picked had barriers of use that we couldn't overcome: the toxicity and light-sensitivity. We spent a large amount of time trying to find a way to make it work and then even longer trying to find a replacement. We decided to go with zinc oxide. Zinc oxide brought with it its own troubles, but they were less significant than the issues with the photoresist. We believe with a few minor alterations, our composition could definitely be successful and it would be an improvement from the model we based our design off of. We believe if we could do the entire printing process, from filling the ink cartridges to the final round of printing and curing, consecutively, our design and process would have been highly sucessful.

Chapter 1

Introduction

Printed circuits have become ubiquitous in the electronics industry over the past few years due to the relatively low cost of production and broad range of applications. The potential for a flexible form factor has made inkjet-printed circuits a popular solution for facilitating the realization of devices such as pressure sensors, radio frequency identification (RFID) tags, solar cells, LEDs, and transistors [9]. The thin film transistor (TFT), a complex printed circuit device, possesses great potential to expand printed circuit functionality. Intel's latest processors contain 100 million transistors per square millimeter. Transistors are what allows computers to do computations; so, at the most basic level, the more transistors that are available to the computer, the better that computer can operate; the computer can do more difficult computations faster. Transistors work using alternating n-type and p-type regions. N-type regions consist of areas in which electrical conduction is caused by the movement of electrons. Whereas, p-type regions consist of areas in which electrical conduction is caused by the movement of holes, which are positive due to a lack of electrons. These areas have terminals (called the source, drain, and gate) to connect the regions to other components. These components then cause the regions to interact with each other, usually pulling two isolated regions towards each other, creating a depletion layer and helping the electrical conductivity, as seen in figure for a metal oxide semiconductor field-effect transistor (MOSFET).

Most wearable devices today currently use conventional monolithic integrated circuits for signal amplification. Modern silicon-based ICs are bulky, expensive to develop and manufacture, and have a slow turnaround which increases the time to market. Printed electronics may increase the durability and reduce the size of wearable electronics. Also, there is tremendous flexibility in transistor-based circuit design using the printing fabrication process because of a much shorter turnaround time.

This project outlines the development and realization of an ink-printed transistor amplifier at Cal Poly. The Dimatix DMP-2831 inkjet materials deposition system is used to fabricate the transistor with various conductive nanoparticle inks. With a minimum droplet separation of 25μ, the Dimatix printer is not able to simply *print* a sufficiently small channel length by jetting the two materials in adjacent positions on the substrate [10]. To yield a channel length on par with modern monolithic silicon transistors, inks in opposing solutions will be juxtaposed on the substrate. Silver nanoparticle inks are used for the gate, drain, and source terminals of the transistor. The channel is made of a semiconducting single walled carbon nanotube material and the insulator between the gate and source/drain terminals is zinc oxide functioning as a dielectric material. High performance transistor device fabrication can be achieved using these materials [11]. While the transistor-based amplifier is the primary focus of this project, the potential for future students and faculty to use the process for printing transistor-based circuits becomes an ancillary goal.

Chapter 2 establishes the basis and inspiration for this project. Chapter 3 covers the requirements and specifications that we set forth to achieve through the project. Chapter 3 describes the resources necessary for the execution of the project and the process of obtaining them. In Chapter 5 the design and design process for the transistor is covered. Chapter 6 chronicles the construction and testing process for the transistor. Finally, Chapter 7 consists of our conclusions and recommendations as to where the project should go in the future.

Chapter 2

Background

2.1 Traditional Transistor Manufacturing

Existing transistor manufacturing processes require specialized equipment and extensive research and development. Once the design for a new transistor is created, it must be sent to an integrated circuit foundry to be fabricated, which can take a significant amount of time. Our project aimed to make inkjet based fabrication of transistors a possibility. The ability to fabricate small numbers of chips for research or teaching uses would enhance the ability to create items. This idea echos the boom that three dimensional printing, using plastic, has allowed virtual designs to become physical prototypes quickly to allow for rapid innovation and problem solving without requiring extensive machinery or other time consuming fabrication techniques. This ability would bring transistor manufacturing to the masses and allow it to be performed in both hobbyist and educational settings.

2.2 Inkjet Transistor Manufacturing

Our aim to to create a transistor using an inkjet based manufacturing process. Our work would replicate and improve upon the research conducted by other groups, such as the one undertaken by a group of researchers at The University of Texas at Austin. This project is the first time a transistor created by this process has been attempted at Cal Poly. Our goal is to print doped material onto a substrate in order to create a functional transistor. A side view of the layout of the source, gate, and drain layers is shown in Figure 2.1 below.

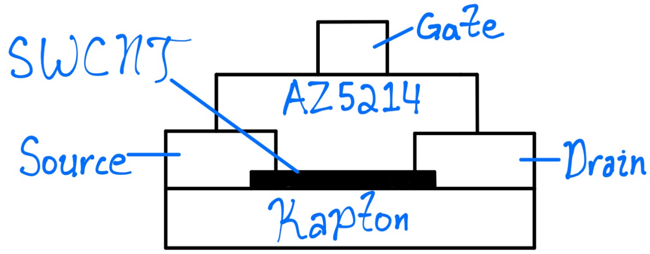


Figure 2.1: A Cross Section of a Top Gate Transistor Design

This method of production opens the possibilities of rapid prototyping for transistors, much like how three dimensional printing has changed the prototyping process for mechanical parts by reducing the amount of manual machining necessary. Our project is the manufacturing process used to create a transistor using an inkjet materials printer. Additionally, this system allows for flexible substrates to be utilized to potentially unlock the ability to have wearable circuity that can conform to the complex and ever changing curves of the human body.

2.2.1 Inkjet Technology

Inkjet printing was developed as a result of an accident in the late 1970s, in which a hot soldering iron touched a syringe that contained ink; the heat from the soldering iron caused ink droplets to spray out the syringe, and thus, inkjet printing was born. Since the 2000s, there have been many successful accounts in which groups have inkjet-printed transistors, but the problem has always been poor performance; most of the performance issues stem from the size of the channel-width. Within the last year, new techniques have been designed to decrease the size of the channel-width and performance now rivals traditional manufacturing processes.

2.2.2 Fujifilm Dimatix DMP-2850

The Fujifilm DMP-2850 is an inkjet printer allows for the deposition of fluidic materials on a substrate with a max size of 8in x 11in, utilizing a disposable piezo inkjet cartridge. This printer is able to create patterns over an area of about 200 x 300 mm and handle substrates up to 25 mm thick. This system enables easy printing of structures and samples for process verification and prototype creation. The unique MEMS-based cartridge-style printhead that allows users to fill their own fluids and print immediately with the DMP. To minimize waste of expensive fluids, each cartridge reservoir has a capacity of 1.5 ml. Cartridges can easily be replaced to facilitate printing of a series of fluids. Each single-use printhead cartridge has 16 nozzles spaced 254 microns apart with typical drop sizes of 1 and 10 picoliters.

Chapter 3

Requirements and Specifications

Some of these specifications below were determined by analyzing industry standards, while other specifications were conducive to more niche applications. Some specifications for the ink-printed transistor amplifier were generated using the IEEE Guide for Developing System Requirements Specifications [12], which uses the customer, environment, and technical community to generate system requirements. Other system specifications derive from research on similar products. The design specifications of the ink-printed amplifier give a broader description of its functionality but function as the high level goals of the project.

3.1 Engineering Requirements

The first and most important requirement is that the device will be printed using a Fujifilm Dimatix DMP-2831 Inkjet Printer as it offers design flexibility with its multi-layer pattern editor program. Requirement two is that the surface area of the substrate that the amplifier is printed on should not exceed 20 x 20 mm^2. This is because the transistor amplifier substrate must have a sufficiently large surface area to remain on the human body with an adhesive layer between the substrate and the user's skin, but not be so large that it is obtrusive. The substrate also protects the user from exposure to current. The amplifier should be able to achieve a gain of at least 40dB as bio-electric signals are typically in the 10μV and 10mV range requiring a large gain to be useful. The fabrication time should not exceed two days as a quick turnaround time means more time to tweak designs and make modifications. The current average custom integrated circuit turnaround time is thirty days.

The production cost should not exceed $10 per unit. This production price point is far less than the industry standard for Application-Specific Integrated Circuits (ASIC). Each printed transistor should have a channel length shorter than 3 microns as high performance transistors in modern amplifiers have sub-micron channel lengths. Printed transistors should have an ON/OFF current ratio greater than 10^6 which is comparable to existing industry integrated circuits amplifiers which use transistors with ON/OFF current ratios in the range of 10^5 to 10^{10}. The amplifier circuit shall be printed on a flexible Kapton substrate. Kapton tape is a conductive adhesive tape that provides flexibility and solid grounding for the printed circuit. The input, output, supply, and ground terminals should protrude from amplifier with leads of length longer than 5mm. The amplifier will need sufficiently large leads for running performance tests and integration with other electronics. The amplifier should have terminals made of conductive silver inks. Silver inks form a conductive film layer when cured. The device should operate in the temperature range $20^{\cdot} F$ $(-6.7^{\cdot} C)$ to $120^{\cdot} F$ $(48.9^{\cdot} C)$. If this amplifier were used in a medical application, it must be able to with- stand extreme temperatures. The device shall not draw more than 10mA of current as this current limit will ensure no harm is inflicted on the user. Current above 10mA can cause pain or injury to humans [13].

3.2 Design Specifications

The device should have a small form factor for optimum user comfort and wearability. It should be made with a high precision materials deposition system using conductive inks. The transistor should be able to amplify small amplitude signals and interface with external electronic systems. The amplifier should have a short fabrication turnaround time with a have a low cost. It should have performance comparable with industry integrated circuit amplifiers and be robust against electrical noise. Finally, the device must operate under a large set of environmental conditions and be safe.

3.3 Engineering Requirements and Specifications Table

Specifications regarding the size, manufacturing process, performance, turnaround time, and cost of the printed amplifier are summarized in Table 3.1 below.

Design Specifications	**Engineering Specifications**	**Justification**
1,9	The surface area of the substrate that the amplifier is printed on should not exceed 20 x 20 mm^2.	The amplifier substrate must have a sufficiently large surface area to remain on the human body with an adhesive layer between the substrate and the user's skin. The substrate also protects the user from exposure to current.
2	The device will be printed using a Fujifilm Dimatix Inkjet Printer DMP-2831.	The Dimatix Printer offers design flexibility with its multi-layer pattern editor program.
3,6	The gain of the amplifier should exceed 40dB.	Bio-electric signals typically in the 10uV to 10mV range require a large gain.
3,6	The amplifier should function with a supply voltage no greater than 5V.	Most standard standalone amplifiers function with a supply voltage rail from 0 to 5 volts.
4	The time required to fabricate an amplifier should not exceed 2 days.	Quick turnaround time means more time to tweak designs and made modifications. The current average custom integrated circuit turnaround time is 30 days.
5	Production cost should not exceed $10 per unit.	This production price point is far less than the industry standard for ASIC amplifiers.

Design Specifications	Engineering Specifications	Justification
4,6	Each printed transistor should have a channel length shorter than 3 microns.	High performance transistors in modern amplifiers have sub-micron channel lengths.
6	Printed transistors should have an ON/OFF ratio greater than 10^6.	Common industry integrated circuit amplifiers have transistors with ON/OFF current ratios in the range $10^5 - 10^{1}0$.
1	The amplifier circuit shall be printed on a flexible Kapton tape substrate.	Kapton tape is a conductive adhesive tape that provides flexibility and solid grounding for the printed circuit.
3	The input, output, supply, and ground terminals should protrude from amplifier with leads of length longer than 5mm.	The amplifier will need sufficiently large leads for running performance tests and integration with other electronics.
2	The amplifier should have terminals made of conductive silver inks.	Silver inks form a conductive film layer when cured.
7	The amplifier should have a differential pair/active load topology.	Differential pair topology has very low common mode gain, a great way to prevent the amplification of noise signals.
6,8	The device should operate in the temperature range 20°F (-6.7°C) to 120°F (48.9°F)	If this amplifier were used in a medical application, it must be able to withstand extreme temperatures.
9	The device shall not draw more than 10mA of current.	This current limit will ensure no harm is inflicted on the user. Current above 10mA can cause pain or injury [13].

Design Specifications

1. Should have a small form factor for optimum user comfort and wearability.
2. Should be made with a high precision materials deposition system using conductive inks.
3. Should be able to amplify small amplitude signals and interface with external electronic systems.
4. The amplifier should have a short fabrication turnaround time.
5. The device should have a low cost.
6. Should have performance comparable with industry integrated circuit amplifiers.
7. Should be robust against electrical noise.
8. The device must operate under a large set of environmental conditions.
9. The device must be safe.

Table 3.1: Transistor Requirements and Specifications

Chapter 4

Resources

4.1 Funding

The development of our version of the inkjet printed transistor had several roadblocks that slowed down the development process. Initially, we realized that additional funding was necessary as the cost of the ink cartridges alone would wipe out our preliminary funding from the Electrical Engineering Department Senior Project fund, not to mention the four other inks that are necessary. This was resolved at the end of winter quarter when we received a CPconnect grant of $1500 allowing us to move forward with the project.

4.2 Lab Space

Finding a location to perform the process also took up much of our time during Winter Quarter. Once we received permission from the Graphic Communications department and Dr. Keif we began to search for a place on campus to store and utilize the the printer for the duration of the project. It was eventually decided that due to the unavailability of sufficient lab space on campus that we could have access to, the printer would be located in our adviser Dr. Tina Smilkstein's office.

4.3 Ink Selection

Once a location for the printer was decided, the final hurdle was finding suitable replacements for the inks that we were unable to acquire. Other teams have successfully created transistors using proprietary solutions of materials to adequately fulfill both the requirements of the materials printer and the requirements of a functional transistor. We based our design upon the work done by a group at The University of Texas at Austin [2]. In addition to the UTdots UTDAg40IJ solvent based and Novacentrix JS-B40G silver nanoparticle inks which were able to source from the manufacture; they utilized a proprietary non-aqueous form of single walled carbon nanotubes and AZ5214 photoresist. We decided to try the process with a new product, released by Sigma-Aldrich, to replace the proprietary single-walled carbon nanotube solution with an off the shelf product. While discussing the project with members of the Electrical Engineering department faculty, it was realized that we would unable to secure sufficient fume hood space and time on campus to be able to utilize the AZ5214 photo-resist as our dielectric material to separate the gate layer from the source and drain below it. The need for a fume hood was due to the toxicity of the chemical itself. The photoresist also had an extreme light sensitivity which complicated handling of the raw materials, cartridges, and in progress prints. Both the toxicity and the light sensitivity make photoresist difficult to work with; it would require a space with either a darkroom or low-ultraviolet environment and a fume hood. Therefore we decided to search for an off the shelf product to replace the AZ5214 photoresist in our design. Finding the zinc oxide to be a potential suitable replacement for the photoresist occurred relatively late in the development process as it was a new product that had just been released by Sigma-Aldrich. After reaching out to various vendors, it was found that we could order both the single walled carbon nanotubes in the intended non-aqueous-based (solvent-based) solution. Unfortunately, by the time we decided that zinc oxide would be a suitable solution to replace the AZ5214 photoresist, the lead time for the solvent based single-walled carbon nanotube solution was several months out; so, we had to switch to a water-based aqueous solution.

Chapter 5

Design

Our manufacturing process heavily revolves around the Fujifilm Dimatix Printer and its ability to precisely jet our inks onto our substrate. We must swap the ink cartridges between the four different materials that we jetted to make up the five different layers of the design. Additionally the printing process includes a curing process between some of the layers in order to make sure that the inks set and are not easily removable from the substrate by scratching them off or mix with other layers while they are still liquid. The curing process also increases the conductivity of the final product. While the design shows five different inks, both the gate and source of the design are made up of the same ink as discussed in Table 6.1 on page 16. The most complex part of this task is having to re-align the substrate onto the print bed after removing the substrate to perform the curing process.

One of the primary challenges in fabricating a transistor is the achievable minimum channel length. Traditionally, inkjet printed electronics creates this gap between the source and drain by merely not printing a space in a transmission line. In theory this yields a gap where the width is limited by the resolution of the printer. Given that a printer like the Dimatix has a resolution of 10–30 μm depending on the selected drop volume, this provides a small gap, but by no means a short channel compared to photolithographic methods in a traditional CMOS foundry. However in practice, during the print process this gap often has to be much larger. This is partially because the print position has have fairly significant error bars, but the affinity of inks employed complicates the issue. If the source and drain were to be printed using the same ink, and the chemical force between the source and drain is greater than the surface energy of the substrate, the ink will pull across the source and drain, causing closure of the gap and creating a short circuit

The key idea that we are attempting to leverage is that oil and water do not mix. The reason behind having two different silver nanoparticle inks. The UTdots AgIJ is comprised of a proprietary hydrocarbon solution (oil based) while the Novacentrix ink is aqueous (water based). This is illustrated if Figure 5.1 When the second layer is jetted since the two inks are oil and water based, the water based ink is intrinsically hydrophilic since it is water and the polar molecules attract each other. The opposing solvent based ink is hydrophobic and non-polar. This means that it will not mix with the aqueous ink resulting in a very small gap, smaller than what could be achieved with mechanical separation of the source and drain when jetting the same ink for both terminals. A small gap can be accomplished with any ink pairing with opposing chemistries, not just silver nanoparticle solutions. By printing the two inks in a single layer side by side, the chemical force would produce the gap as shown in Figure 5.1. In the printing process, the two ink sections were printed right next to each other with no gap from the printing process. This method has the added benefit of being highly reliable. Rather than relying on a mechanical process, this strategy relies on a chemical process which should be consistent as long as the composition of the inks stays the same. Therefore, it is possible to print this gap much smaller without having conduction between the two sides of the gap while still maintaining acceptable print reliability

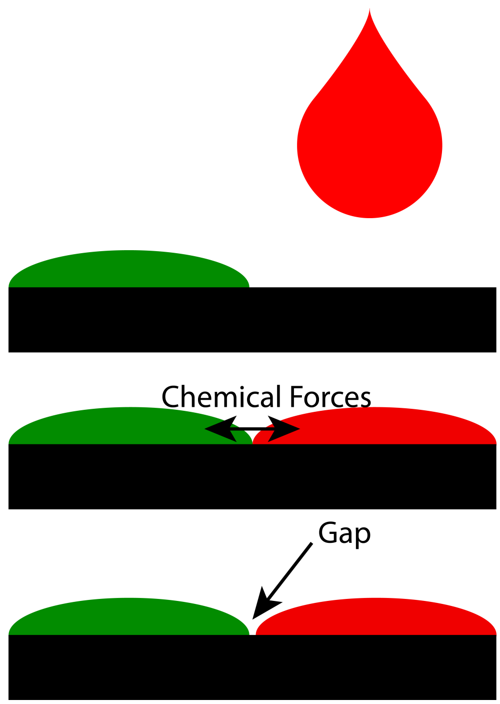


Figure 5.1: Illustration of the chemical forces between the inks.

We based our design upon the design utilized by the team at The University of Texas at Austin as our jumping off point. Our initial design concept is shown in 5.2 on page 12. Figure 5.3 on page 12 is an exploded 3D rendering of our design showing how the layers interact with each other in 3D space. Each layer is printed on top of the previous layer(s). The bottom layer shown is the Kapton substrate. The small black square is the single walled carbon nanotubes as shown in Figure 6.4a to form the channel. The two side by side layers grey shown above the single walled carbon nanotubes are the source and drain made of silver nanoparticle inks of different chemistries as shown in Figures 6.4b and 6.4c. The space shown between the two is shown larger than reality to emphasize that a gap exists between the source and drain. The translucent layer above that is the zinc oxide layer shown in Figure 6.4d. When printed the layer is meant to flow down into the channel between the silver inks and ensure that the gap between the source and drain exists. This layer also isolates the gate from the source and drain so that they do not short out. The final grey top layer is the gate made of silver nanoparticle ink as shown in 6.4e. Since this is just a printed layer there is no need to leverage the hydrophobic or hydrophilic properties of the ink.

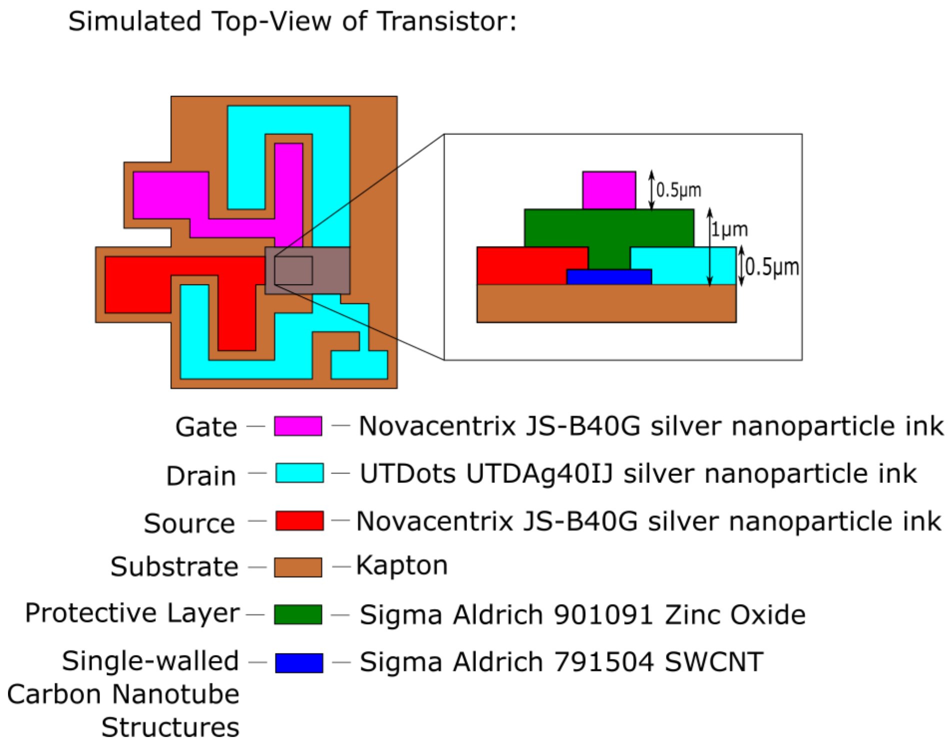


Figure 5.2: Simulated Top View of Preliminary Design Option

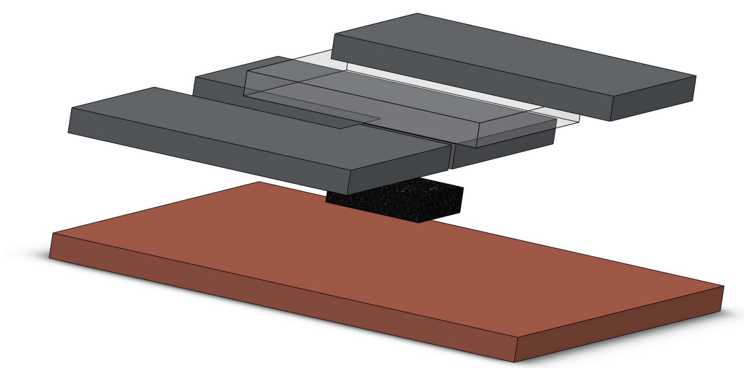


Figure 5.3: Exploded 3-D Rendering

Chapter 6

Construction and Testing

6.1 Printer Preparation

We worked alongside another group working with the Dimatix printer to learn the process of using the printer and how to create pattern files from Dr. Keif of Cal Poly's Graphic Communications department. This involved setting up the printer and figuring out what was necessary to control, clean, and print on the Dimatix. We encountered some issues with ensuring that the correct cleaning pad was in place during all cartridge swap to avoid contaminating the jetting module. Time was also spent learning what sequences of actions could cause the control software or printer to crash. In most cases this occurred if you attempted to move too quickly between modes without allowing the print head and bed to complete the move instruction in progress before issuing another command.

6.2 Filling Cartridges

After getting comfortable with the printer utilizing cartridges and inks that were in stock we moved on to attempting to print with our real materials. With the assistance of Dr. Keif, we were able to fill four ink cartridges with our selected inks, seen in Figure 6.1. The filling process involves

Figure 6.1: Each of the four inks in Manufacture's Packaging

drawing the ink out of the manufacture's packaging using a syringe and needle, then a filter is added to between the syringe and the needle before injecting the ink into the cartridge. During the filling process for the cartridges, it was realized that we would have issues jetting the carbon nanotubes as they would not push through the filter, shown as the white disk on the left side of Figure 6.2 on page 14, used to fill the Dimatix ink cartridge. When enough force was exerted upon the single walled carbon nanotube solution, only water would make it through the filter with very few if any carbon nanotubes making it through the filter to the cartridge. We opted to fill the cartridge directly without a filter, however this lead to issues with the jetting process. We discovered during the printing process that the single walled carbon nanotube segments were too large to always jet reliably.

Figure 6.2: Supplies for filling a DMP 2831 Cartridge

Due to the expensive nature of the ink-cartridges we opted to remove two of the retention tabs from the cartridge that prevent the cartridges from being refilled. This contributed to some leaks of inks from the connection between the reservoir and the print head assembly during storage, however it allowed us to be able to re-use spent cartridges for future prints only needing another syringe and filter, which are much cheaper than a new fluid module and print head.

6.3 Calibration

The printer has a several points where it needs to be calibrated. It performs an automatic calibration of the x, y, and z print arm, and of the onboard amplifiers in the print system every time that the printer is powered on with no interaction from the user being necessary.

6.3.1 Jet Voltage

During preparation for the printing process, it is necessary to select which of the sixteen nozzles to utilize and to adjust the voltage applied to the selected nozzles during the jetting process in order to make sure that all of the selected print heads are jetting the same amount of ink simultaneously. These profiles can be saved per cartridge, however selection of jets should be performed before every print. The Dimatix DMP-3831 has a drop watcher camera to assist in the calibration process. A screen-shot of the calibration process is shown in Figure 6.3 on page 15. The drop watcher allows the system setting to be altered to achieve good drop formation, select the largest consecutive series of working nozzles, and to align the drop velocities for the chosen series of working nozzles. One of our biggest problems was that debris and solidified ink would clog the nozzles and prevent proper operation. The printer also features a cleaning process that can be setup from with in the drop watcher, however this did not always do enough to clear all of the obstructions once the debris had solidified. This self cleaning feature can utilize the system's built in cleaning routines, or utilize a custom routine depending on the ink in use. The cleaning pad can be swapped during the cartridge swap procedure to suit whatever ink is being used and the cleaning routines can be modified during the jet voltage setup. The jet calibration is not necessary to perform before each print as the configuration can be saved. However, one should verify calibration before each print as the jets can clog or otherwise change while the cartridge is being stored.

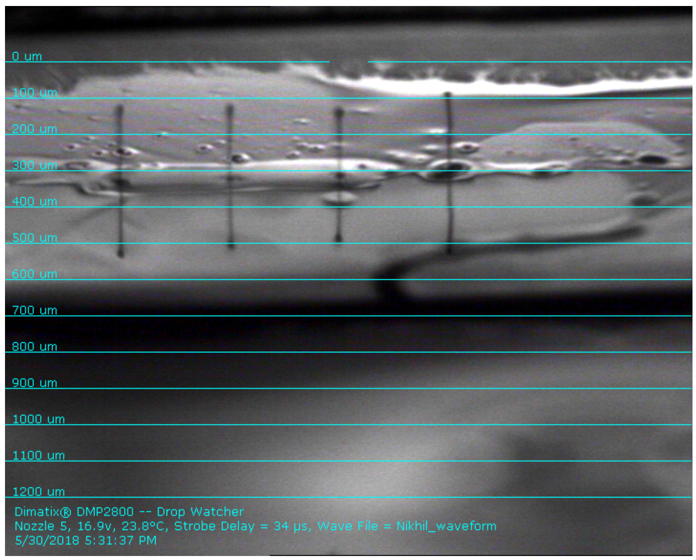


Figure 6.3: Drop Watcher Camera view of UTdots Ink

6.3.2 Jet Selection

Each time that a cartridge is used the drop watcher camera mentioned in the Jet Voltage calibration section is utilized to select a number of usable print jets. The usable print jets must be consecutive so that the resolution of the print is not affected. The drop watcher camera allows you to move the print cartridge left and right in order to view all of the jets while enable and disabling jets to determine four to five out of the sixteen possible jets are to be utilized during the print process. This process should be repeated before each print as the jets are temperamental and different sets of jets will provide better performance depending on a variety of environmental factors.

6.3.3 Saber Angle

Additionally, the saber angle can be adjusted to adjust the angle. The saber angle allows you to rotate the print head in relation to the build platform. As the saber angle increases the print resolution increases, however drops can begin to flow onto one another as each resolution cell gets closer to the others. All of your prints were performed at a low saber angle to compromise between having space between drops and over saturating our substrate with ink and it beginning to run. The saber angle is not electronically actuated so it must be manually set by releasing the clamp on the print arm and rotating the cartridge mounting assembly to the desired angle. The printer's onboard fiducial camera assists in the calibration of the saber angle by allowing a user to look at the printed pattern to see if the droplets are close enough together to be electrically conductive, if the area appears flooded, or the correct resolution cell alignment has been achieved.

6.4 Bitmap Creation

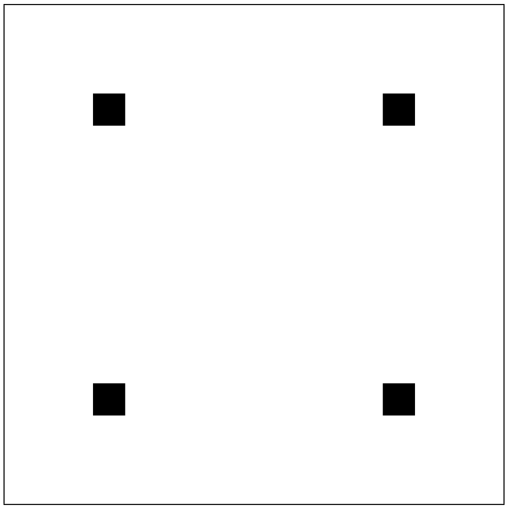
We simplified the design in order to reduce the printing time and reliability from our initial idea concept shown in Figure 5.2 on page 12. Our printer files are shown in Figure 6.4 on page 17. These are printed on top of each other in the order listed. The printer files pictures are setup to print four transistors in one printing round due to allow for possible defects in the print process. The designs were created in Adobe Illustrator and exported as bitmap files. Adobe Illustrator was selected to create the pattern because of it ability to show each of the inks in layers and then export them, dynamical scale all components, and export a 1-bit bitmap. One of the hurdles with the design created in AutoDesk's AutoCAD was that it exported a full color bitmap which is incompatible with the Dimatix printer file creation process.

6.5 Printer File Creation

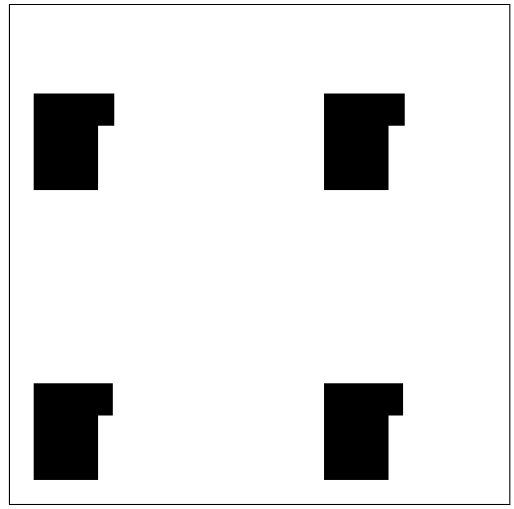
After the 1-bit bitmap was created, these files were then imported into the Fujifim Dimatix software on the print computer to create the print instructions. The printer requires a true bitmap where the only available options for each pixel are white or black. Greyscale and Color images are not compatible with the Dimatix software. We needed to utilize a bitmap file because we did not have the optional $1200.00 Vector Graphics Format Conversion Software package installed on the printer computer to intake AutoCAD or Gerber files which are exportable from most electronics CAD software. We had access to alternative software that would create a very high quality bitmap which mean that this did not affect the quality of the print. Therefore we did not decide to go down the path of obtaining the software package, however it did mean that the additional step of rasterizing our design before sending it on to the printer was required. Our printer files are shown in Figure 6.4 on page 17 with the composition of the layers noted in Table 6.1. During printer file creation the number of passes the print should be performed over is set.

Layer #	Layer Description	Ink
1	Single Walled Carbon Nanotubes (Channel)	Sigma-Aldrich 791504
2	Source	Novacentrix JS-B40G
3	Drain	UTDots UTDAg40IJ
4	Oxide (Channel)	Sigma-Aldrich 901091
5	Gate	Novacentrix JS-B40G

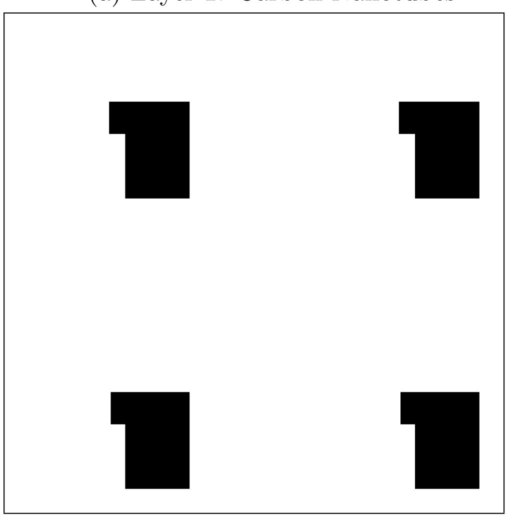
Table 6.1: Printing Layers



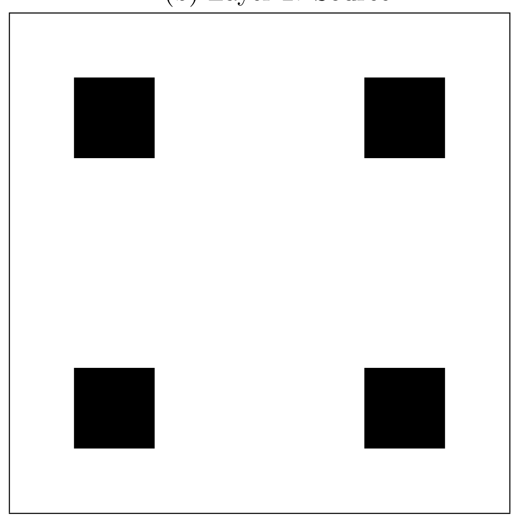
(a) Layer 1: Carbon Nanotubes



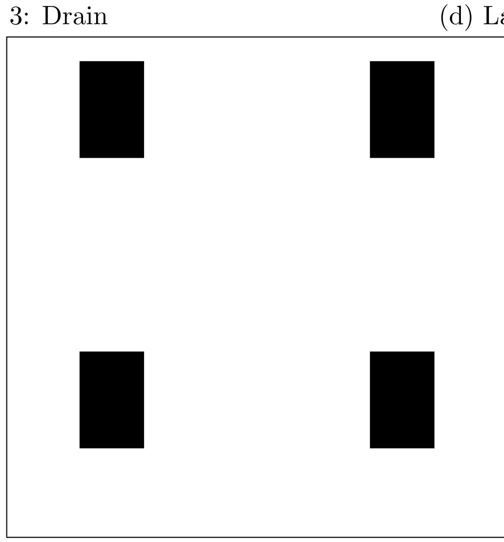
(b) Layer 2: Source



(c) Layer 3: Drain



(d) Layer 4: Oxide



(e) Layer 5: Gate

Figure 6.4: Final Printer Pattern Files

6.6 First Print

Our first attempt at a complete print was performed in one step. We did not dry the layers between layers. This decision caused the oxide to mix with the source, gate, and drain closing the desired gap. This was the original methodology to avoid having to re-align the substrate between the printing and curing process.

Figure 6.6 shows pictures taken with the Fiducial Camera between passes during the printing process. Figure 6.6a shows layers one and two being printed. The overlap between the carbon nanotubes in dark grey and silver nanoparticles in black is noticeable with the textured and lightest color being the Kapton substrate. The camera is black and white hence the orange color of the Kapton is not visible. In Figure 6.6b we can see the interaction between the two inks after layer 3 has been jetted.

6.6.1 Testing

When testing our first print, initially our transistor showed decently promising results, especially for a first draft. During testing we did notice that the single walled carbon nanotubes seemed to be printed very lightly. Unfortunately, since we did not cure the first print, the more we attempted to test the device, upon connecting the ink pads to the test equipment, the more the ink smeared. The smears caused gaps in the ink and destroyed the composition of our print, which made further testing futile for that print. However, this print was successful in proving that we had properly filled all of the ink cartridges and that we had a printable pattern. This print also solidified the idea that we did need to cure the ink after printing the source and drain. We also concluded we need to do multiple deposition passes for the single-walled carbon nanotubes and the aqueous silver-nanoparticle ink. We came to this conclusion because of how light the single-walled carbon nanotube layer appeared and the aqueous silver-nanoparticle ink had some continuity issues; we believe adding a deposition pass fixed these issues in the second round of printing. The results of this first print are shown in Figure 6.5 with all of the layers successfully printed they could be examined on the printer's fiducial camera between layers.

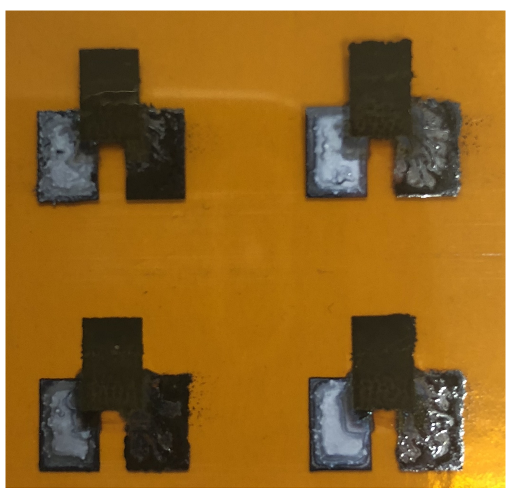


Figure 6.5: First Print

6.7 Second Print

Our second print went fine for the initial layering with some indications that the carbon nanotube cartridge was having issues jetting. The main issue is due to the fact that we did not realize that we needed to order a much finer blend of carbon nanotubes in order for them to reliably jet through the Dimatix cartridge. Unfortunately, Sigma-Aldrich did not offer a different size of carbon nanotubes, only different strengths of mixtures.

Additionally, we were plagued with issues when we returned from curing such as the ink cartridges for the oxide layer drying up due to the time between printing sessions, sharing the printer and cartridgeswith another group who altered the setup to suit their needs, and having trouble getting the printer to align correctly. The zinc oxide did its job as an insulating layer, however due to its translucent appearance and tendency to very quickly dry out it was difficult to verify that enough of the jets were reliably working and if the alignment of the substrate was performed correctly. A change in the printer's home position between prints resulted in the pattern being printed in the incorrect position and partially on the print bed itself. The excess ink was wiped off of the print, however the alignment used before the curing process could not be recovered rendering the print unusable.

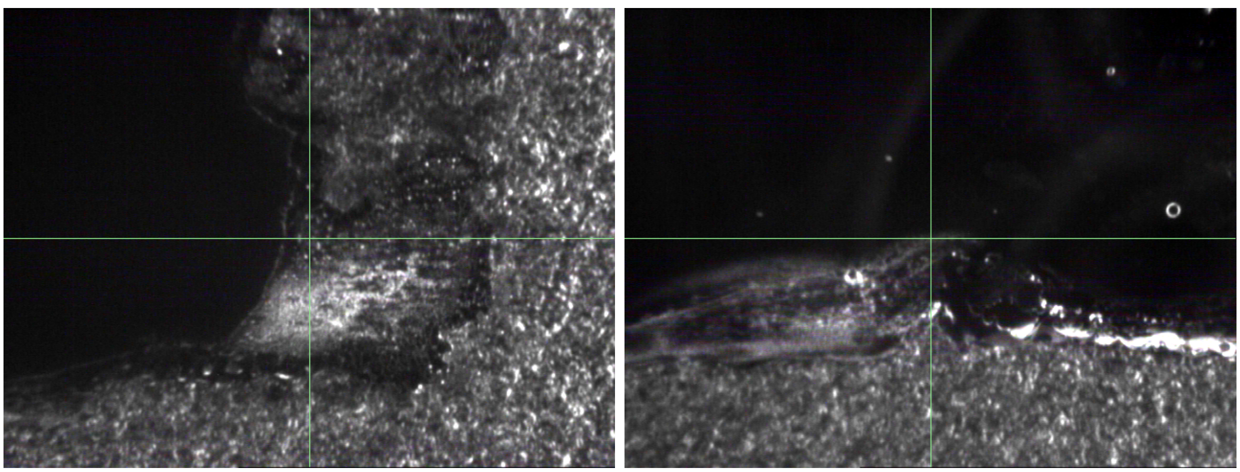
6.7.1 Testing

The initial testing for the second print had positive results. We printed the first three layers (single walled carbon nanotube solution, the source, and the drain). We then cured that print at 200 degrees Celsius for thirty minutes. For this test, we simply were looking the the resistance between the source and the drain. We measured the resistance as five to ten ohms; we believe this resistance is reasonable for two silver pads separated on the nanometer scale.

Unfortunately, we ran into printer issues. Our time conflicts with lab open hours equated to the need to wait overnight in between print layers, which caused the ink in the ink cartridges to dry up and clog. We tried to fix the clogged cartridges, but could not successfully clear the nozzles. We believe if we could fill the cartridges and immediately do all printing and curing, we would have had a successful transistor. We also faced issues when returning to print after curing. It was difficult to realign the printer and substrate perfectly; we needed it in the exact same place as before. We believe this problem could be remedied by placing multiple layers of tape around the edges of the substrate, so it would sit perfectly in the rectangle of tape, then when we returned from the curing process, we could have an indintation in which to place the substrate.

Had we been able to complete this print, we would have tested the continuity of the print to ensure we had a successful ink deposit. After that, we would have set up basic circuits and tested basic transistor parameters, including: collector-emitter voltage (with base open circuit), collector-base voltage (with the emitter open circuit), emitter-base voltage (with collector open circuit), collector current, peak collector current, peak base current, total power dissipation (at 25 degrees Celsius), junction temperature, collector-base cut-off current, emitter-base cut-off current, forward current gain, collector-emitter saturation voltage, base-emitter saturation voltage, collector capacitance, emitter capacitance, and transition frequency.

After we determined the characteristics of the transistor, we would have observed and noted how it performed in basic amplifier operations. Once we were satisfied with our results, we would have printed multiple transistors and tested the yield rate of our printing process. We then would have looked for methods to improve our design. We will be continuing work on this project in the future with another set of prints with a better system for alignment system.



(a) Carbon Nanotubes and Source (b) Bottom Right of Channel

Figure 6.6: Fiducial Camera View of Selected Regions of Print

Chapter 7

Conclusions and Recommendations

While we were able to successfully print, Sigma Aldritch's Zinc Oxide for inkjet printing is not a fully drop in replacement for the photoresist used in the paper that we are modeling. It dried up in the cartridge and caused all sorts of jetting problems. In the future the Zinc Oxide may need to be continually kept refrigerated in between prints even though it is rated to stay fine at room temperature. It would also be benificial to determine a better way to clean the cartidges in case we are faced with this issue again. We also attempted to utilize an aqueous carbon nanotube solution. However we encountered the problem that our carbon nanotube solution has too large of carbon nanotubes to be reliably jetted. The process was promising with initial probing of our test prints indicating semiconductive properties before we damaged the print

Future print rounds should utilize a smaller pitch of carbon nanotubes to increase jetting performance. Once again, it is possible that a better cartridge cleaning method would solve this problem as well. Additionally a solvent based solutions such as the one utilized in the University of Texas Austin article may provide better jetting performance. Solvent based carbon nanotube solutions do exist commercially, however in our case had a prohibitively long lead time. Additionally, in the next design round a better methodology for aligning prints needs to be devised possibly by jetting out a calibration mark that can be aligned with the build platform after the curing process takes place. The viability of zinc oxide as the separation layer should be further investigated. We were disappointed in the performance of the zinc oxide as an ink since it was marketed as being for inkjet printing we did not expect it to dry out when left in the cartridge overnight. If given more time and capital, it would have been nice to test out different inks for all pieces of our transistor; unfortunately, the inks and ink cartridges are expensive, so purchasing ink simply to test if it would work well was not in our budget. Time also created a significant problem for us. We started to make extremely large strides in the last month or two of working on this project, after we made the decision to used zinc oxide as the dielectric, but because this discovery was made so late, we couldn't fully capitalize it. We believe before anyone attempts to further work on this project, they should attempt more research to obtain a way to clean the ink cartridges. The solution could be as simple as removing the top of the cartridge and shooting distilled water through the nozzles at a high-power and using plastic wrap to seal the bottom of the cartridge and storing it in a better enviornment.

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Appendix A

Analysis of Senior Project

Adviser: Dr. Tina Smilkstein

A.1 Summary of Functional Requirements

The goal of this project is to create a MosFET transistor using an inkjet manufacturing process on a wearable substrate. Each of the transistors was tested to measure their performance and to determine the viable yield rate of the process. We will documented our design and detail the process and necessary inks to create each of the layers that make up a transistor. Our findings will provide insight for both the research and development of new transistors and allow rapid prototyping of transistors for a wide variety of customers. The amplifier will be printed with various nanoinks, photoresist, and carbon nanotube materials using the Dimatix DMP-2831 inkjet printer. A developed method to efficiently fabricate custom transistor-based circuits at Cal Poly also has potential as a learning and research tool for both students and faculty on campus.

A.2 Primary Constraints

The primary challenges in this project are to create the necessary ink solutions for each of the regions of the transistor and to create a viable transistor design to be printed by the inkjet materials printer. One of the most difficult challenges imposed by printed transistor fabrication is achieving a channel length small enough that yields performance on par with conventional monolithic silicon transistors. Conventional ICs have transistors with channel lengths well under a single micron. The design of the transistor will be determined by the limitations of the materials printer and inks selected and will need to balance the needs of a transistor design and what the printer will be able to create. The Dimatix DMP-2831 inkjet printer on Cal Poly's campus is capable of printing two separate materials 25 microns apart from each other. To achieve a micron to sub-micron channel length, materials with different chemical properties must be used to chemically set the gap between gate, source and drain electrodes. The ink solutions are specialized chemicals that must be chosen to work together so that they will not run together on the substrate when printed; one shall be solvent based and the other shall be water based. They must also be able to stand up to the inkjet process.

A.3 Economic

The ink-printed transistor amplifier can introduce potential cost savings for on campus electronics research. On a larger scale, electronic hardware companies that adopt printed transistor circuit topologies can drastically cut manufacturing costs and fabrication time. These benefits apply to both the producer and the consumer. The costs of implementing this project are weighted heavily in the materials acquisition. The materials needed to produce working printed transistors cost between $110 and $685 in their smallest quantities (see Table B.1 on page 28). With the Dimatix DMP-2831 inkjet printer able to deposit 1 to 10 picoliter drop sizes, the potential number of transistors fabricated from the minimum quantity of materials can be quite large assuming each transistor will only require a few drops of each material. The cost of a single transistor-based amplifier printed on a wearable substrate, then, is drastically cheaper than ordering custom ICs from a large-scale manufacturer. The cost of the project are outlined in Table B.1 on page 28 of this document. Estimated labor costs take up most of the project cost due to valuing the researcher's time at $30/hour, which was on par with the hourly pay of an undergraduate engineering internship. The long-term payout of this project will not be direct income from product sales but will come from cutting the high costs and turnaround times associated with custom IC fabrication by 3rd party manufacturers. Depending on the circuit design, ink-printing circuits should take no longer than two days. This fabrication time is significantly quicker than the industry average 30-day turnaround. Maintenance costs associated with this project are tied to upkeep of the Dimatix printer and the reordering of materials when supply gets low.

A.4 Manufactured on a Commercial Basis

Our product is both the transistor that we design and the process and ink we develop. Because of the impact on the design and creation of transistors it has the ability to affect the integrated electronics market. The results of our testing will show that inkjet printed transistors can rival the capabilities of traditionally manufactured transistor. Once the idea catches on, the amount of mutations of the process, such as trying different materials, will increase. Once big companies, such as Texas Instruments and Hewlett-Packard, put their resources into exploring the manufacturing process, the process will be perfected and the transistor capabilities will make previous methods completely obsolete.

A.5 Environmental

The environmental impacts associated with the ink-printed amplifier are involved mostly with manufacturing and materials production and are not directly a result of fabrication. Shipment of materials to the Cal Poly campus requires the use of trucks, planes, and trains that all use fuels that emit harmful emissions. Negative consequences of manufacturing the nanoinks and Kapton substrate such as factory-generated pollution of surrounding natural ecosystems may also exist. However, there may be an application for these amplifiers in the energy industry as part of the electronics inside solar panels or wind turbines, for example. Conventional monolithic silicon fabrication is a subtractive process, producing chemical waste during manufacturing as layers are etched away to create various circuit topologies. Fabricating printed electronics, however, is an additive process and generates no chemical waste [20]. Since the primary focus of this project is to improve wearable electronics and sensors, species close to extinction could benefit from wearing these sensors to track their location and health vitals. The data from the wearable sensors could be used by humans to help the endangered species grow again. There are some issues with disposal of nanoparticle waste and the sharps waste created by the inkjet cartridge filling process as they cannot be processed with normal garbage.

A.6 Manufacturability

Manufacturing the ink-printed transistor amplifier will not be too difficult for large-scale electronics manufacturers, since processes in place for manufacturing printed electronics already exist. Printing the transistor amplifier on campus will prove difficult on a large scale, because only one Dimatix inkjet printer exists on campus. This constrains on-campus custom electronics printing to use by only electrical engineering students and researchers. The process of printing with the Dimatix printer introduces challenges such as setting a sufficiently small channel length in the transistor and yielding consistent, reliable, products.

A.7 Sustainability

Requirements for maintaining the ink-printed amplifier will be very similar to maintenance requirements of other integrated electronic components. This means measures should be taken to prevent damage caused by electrostatic discharge and extreme operating temperatures. Sensors that use the ink-printed transistor amplifiers should not be used indefinitely because the operating lifetime of most current printed electronics is no more than two years [21]. Material used to fabricate printed electronics require low temperature processing, giving them greater environmental sensitivity. To overcome this, a protective layer may be added to the transistor to ensure product longevity. Electronics made using the inkjet-printing process on Cal Poly's campus can be reused by students in future courses to eliminate waste of the materials used to fabricate the circuits. Acquisition of more expensive nanoinks with improved chemical properties and a more precise materials deposition system (printer) could be a way to improve the performance of transistors fabricated with an ink-printing process at Cal Poly's campus. The issue with improving the design in this way are greater up-front costs and fabrication expenses.

A.8 Ethical

One outcome of this project is providing an educational tool for electrical engineering students and researchers at Cal Poly. This outcome appeals to the ethical principle system of ethics which is based on four moral principles: autonomy, non-maleficence, beneficence, and justice. The students will gain a sense of autonomy in their coursework with less constraints on electronic design. Basically, they will have the freedom to design their own ICs instead of dealing with constraints imposed by the discrete parts provided in lab kits or by IEEE on campus. Both non-maleficence and beneficence are promoted by this project with students having an educational tool to increase their knowledge and experience in integrated circuit design. This project also appeals to the IEEE Code of Ethics number 6: to maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations [21]. Students at Cal Poly are improving their technical competence by designing and making physically realized printed electronic circuits as a part of their coursework or research. The lab coursework at Cal Poly is what gives students the 'qualification' by training or experience mentioned in this IEEE ethical code. An ethical challenge that could arise with the ink-printed transistor amplifier project could be students stealing the printed electronics made by other students. This challenge could be avoided by requiring students to label their printed electronics with their initials.

A.9 Health and Safety

Inkjet based transistors themselves pose no harm, however the inks have special handling and disposal procedures in order to keep individuals safe. If the transistors are used in a medical or life threatening manner we must be sure that the system is designed such that it would fail safe and have enough confidence in the transistors to not fail in the first place. Our materials are not known to be dangerous, however the Material Safety Data Sheets advise that they not be ingested, inhaled, or prolonged skin contact with.

A.10 Social and Political

Companies using the ink-printed transistor amplifier that make medical devices must ensure that all FDA regulations and guidelines are considered in their designs and manufacturing. Not adhering to government-imposed electronics regulations can severely harm a company's image, resulting a financial trouble for stockholders and employees. More importantly, companies who will used the ink-printed amplifier in their designs must ensure their product does not harm any consumers. The availability of most consumer electronics is limited by their cost and this product may not be accessible to those who cannot afford it. For the on-campus research aspect of the ink-printed circuits, those who do not attend or work at Cal Poly will not have access to the benefits provided by this project. Perhaps the success of this project at Cal Poly could be followed up by having it implemented at other educational institutions with electrical engineering programs to increase access to printed electronics.

Appendix B

Bill of Materials

Manufacture	**Item**	**Quantity**	**Description**	**Cost**
Sigma-Aldrich	791504	1 (25ml)	Carbon nanotube, single-walled, conductive aqueous ink, SWCNT 1.00 mg/mL	$216.00
Sigma-Aldrich	901091	1 (25ml)	Zinc oxide ink for inkjet printing	$190.00
NovaCentrix	JS-B40G	2 (50ml)	50mL of Metalon silver inkjet for Dimatix and XAAR printers	$338.00
UTDots	UTDAglJ	1 (25ml)	Silver nanoink in solvent for inkjet printing	$498.80
DuPont	Kapton	1 Roll	Printing Substrate	$19.00
Fujifilm	DMC-11601	1	10 pack of Dimatix Materials Cartridges 1pL with 10 cleaning pads and 10 fill tips	$990.00
Fujifilm	SYR-003	1	Dimatix Filling Syringe (pack of 10)	$8.00
Fujifilm	FIL-001	1	Dimatix Filter (pack of 10)	$45.00

Table B.1: Bill of Materials