CHAPTER 5

FEEDBACK: LOW START-UP VOLTAGE AND LOW POWER DISPLAY

5.1 Introduction

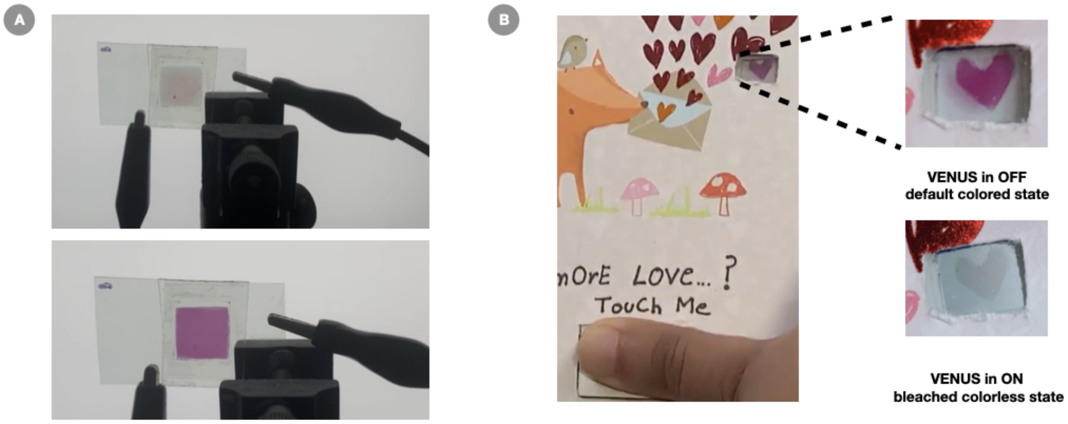


Figure 5.1: VENUS display: a. Theory of operation is based on the phenomenon of electrochromism that results in a change of color due to redox reaction when voltage is applied b. VENUS display as part of a greeting card that changes color on touching

In the previous chapters, I have made iterative additions to the functionality of the sustainable interactive wireless stickers while maintaining the system design parameters of power, cost, and form factor. I first added sensing (chapter 3) with SATURN and other flexible sensors, followed by wireless communication (chapter 4) with ZEUSSS and MARS. In this chapter, I look deeply at how visual feedback can be provided by interactive stickers. Relaying to the user when the interactive sticker is in active operation or communicating is a piece of important information for the user, both from a usability and privacy standpoint. One way to provide feedback to the user is the addition of a visual display. A display suitable for sustainable interactive wireless stickers should maintain characteristics in line with the power, form factor, and cost system constraints; yet, it should be functionally sophisticated enough to provide visual feedback. I describe these characteristics in detail below.

1. **Functionality**
    (a) **Vibrant color changes:** Usually, with low power, the functionality of the device is expected to reduce, yet the minimal functionality that is needed for sustainable stickers is that of an on/off indicator.
    (b) **Reasonable switching speed:** The display should support a change of state in sync with the human speed of actions. Given that the average time taken to perform micro-interactions is 1-3 seconds [17], the display can take roughly 1 second to switch from one state to another and does not need to have an extremely fast switching speed, which is often power consuming.
2. **Power**
    (a) **Low startup voltage (~0.5V) and power (10 μW) of operation:** Display should be able to operate in a sustainable system where power is limited and often only available in short bursts at low voltages due to the inherent nature of the power harvesters.
3. **Cost**
    (a) **No power management circuitry:** MARS achieved this goal in conjunction with low-startup voltages by eliminating the complex power management circuitry. For the display to be part of a sustainable interactive wireless sticker, it should be low-voltage operation and seek to use less silicon and, thus, lower cost overall.
    (b) **Simple fabrication process:** The display should be easy to fabricate and be designed with inexpensive base materials to allow for an overall cost-effective prototyping and manufacturing process.

4. **Form factor:** The selection of display technology should support a thin, lightweight, and preferably flexible form factor.

Based on the above guidelines and the discussion in subsection 2.4.4, where I compared three alternatives for passive non-emissive display technologies that have been previously employed for low-power systems, I will be exploring ECD in this chapter. ECDs have the lowest on/off switching operation voltage among the three alternatives (LCD, EPD, ECD) and are suitable for sustainable interactive systems.

I introduce **V**ibrant **E**lectrochromic-Display with **N**ano-ITO for **U**ltrathin **S**elf-sustainable-system (VENUS), a new type of ECD display that is specifically optimized for providing functionality with power, cost, and form factor constraints. It leverages the phenomenon called electrochromism which is defined as the reversible color change induced by an electrochemical redox reaction. This chapter makes the following contributions:

1. **Device design and simple fabrication for VENUS display:** I explain how VENUS' device design is an improvement over the traditional ECD, allowing it to fulfill the design requirements laid before, including vibrant color change and low power. We further explore its simple fabrication process and unique switching on/off behavior.

2. **Powering and interaction design for controlling different behaviors of VENUS:** I suggest a gamut of ambient power harvesting strategies that can power VENUS and corresponding interactions for on-demand switching.

3. **Exploration of application space:** I explore VENUS as feedback for self-sustainable systems such as a greeting card display powered by hand, and an on/off indicator in an ambient light powered wireless communication system.

In the rest of the chapter, I explain the theory of color change, device design, and working of VENUS display in its various states – oxidized, reduced, and default (section 5.2). It is followed by VENUS display's fabrication process (section 5.4). Next, I explain modes and types of VENUS displays which can help convey different types of information. I elucidate powering strategies possible for the low-power display that are suitable for a display in a sustainable system (section 5.6). Further, I design interactions to switch different modes of VENUS display guided by the power harvester's operating principle (section 5.7). Finally, I explore application use cases for the display part of a self-powered interactive system (section 5.8).

5.2 Theory of Operation for VENUS display: Electrochromism

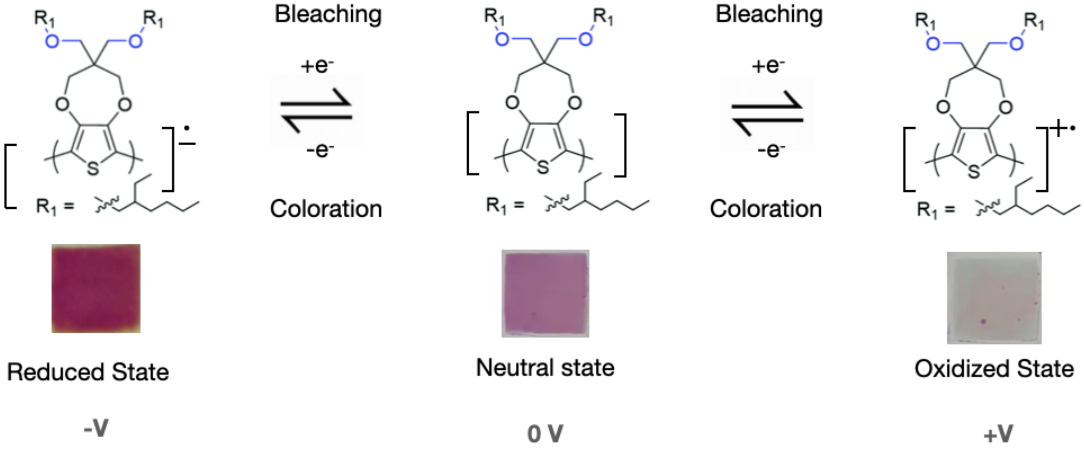


Figure 5.2: Theory of operation: An example of a conjugate polymer, ECP-Magenta, changes its color by applying +/- V due to a redox reaction.

An electrochromic material is one where a reversible (non-emissive) color change takes place upon electrochemical reduction (gain of electrons) or electrochemical oxidation (loss of electrons) in response to an application of an appropriate electrode potential or cell voltage [124]. Materials that exhibit reversible electrochromism are conjugated organic polymers, viologens, and other small conjugated organic molecules, inorganic-organic hybrid materials such as metallo-supramolecular polymers, and transition metal oxides [10]. These materials can all switch between different oxidation states with distinct colors on the application of voltage potential (see Figure 5.2). For example, ECP-Magenta is a type of conjugate polymer that is widely used because of its low working voltage and long-term stability. It is light pink colored in the charge neutrality state and switches to a colorless state upon electrochemical oxidation by applying positive voltage potential. On the opposite side, it turns brighter pink when electrochemically reduced further with a negative voltage. Not all EC materials change state from colored to colorless; some change from one color to another [201]. Such color changes in an electrochromic device can convey useful information to the user through visual signals. Next, I will explore electrochromism as part of the VENUS display device design, where the focus would be to achieve color change with the design parameters of a display for a sustainable wireless sticker.

5.3 VENUS Device Design

In this section, I will first explain the traditional basic ECD device design. Next, I will explain how VENUS optimizes these parameters by modifying the counter electrode design with nano-ITO and working electrode with ECP-Magenta, thus opening avenues for VENUS displays to be included in a self-sustainable system.

5.3.1 Traditional ECD Design

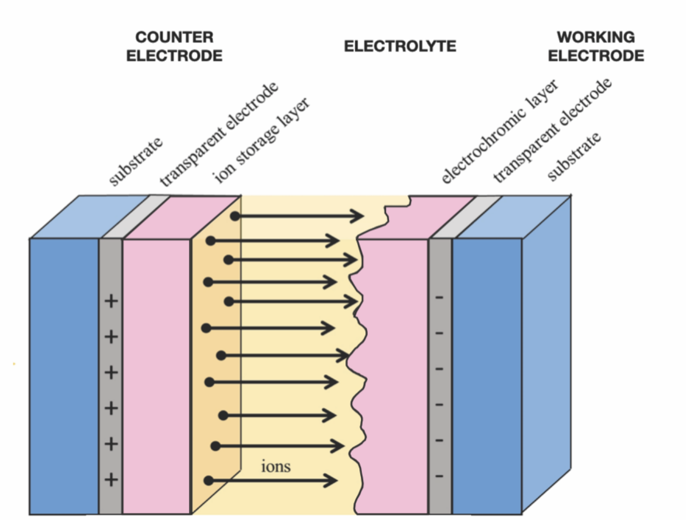


Figure 5.3: Selection of ECP-Magenta conjugate polymer as working electrode based on voltage of onset and clear

A typical ECD operates as a rechargeable electrochemical cell, usually containing two electrodes separated by a layer of electrolyte (Figure 5.3). The device components and their functions are described in detail below:

- **Working electrode (WE):** An electrochromic material layer on a conductive substrate together acts as the working electrode. The EC material is chosen based on color, stability, and power requirements. Transparent thin substrates like PET or glass are used with a transparent conductor coating. The most commonly used conductor is indium tin oxide (ITO) because of its low sheet resistance ($< 10\Omega/sq$), high optical transparency throughout the visible range ($> 80\%T$), and electrochemical inertness over a sufficiently large voltage window for most EC materials.
- **Counter electrode (CE):** In a typical ECD device, the CE, called ion storage or charge balancing layer, compensates (counters) the potential of the WE primarily by double layer formation through a Faradaic process or a combination of both capacitance and Faradaic processes. In particular, the charge balancing of the EC reaction in a device is crucial for the stability and low-power consumption of the EC device. This layer can be EC material that alternatively changes color with working electrode or an optically transparent metal oxide like WO_3, TiO_2, V_2O_5.
- **Electrolyte:** Sandwiched between these two electrodes, a transparent ion-containing electrolyte is transparent and can be in liquid, gel, or solid form. The electrolyte allows for the movement of ions between electrodes during redox reactions, facilitating state transitions.

The ECD device undergoes electrochemical oxidation and the other a reduction when a voltage difference is applied between the electrodes; the gain/loss of electrons is counterbalanced by the movement of cations and anions to the respective electrodes through the electrolyte to maintain charge neutrality.

Unlike a 3-electrode electrochemical device, the role of the CE is particularly important in ECD, which is a 2-electrode electrochemical device, due to the lack of a non-polarizable reference electrode. This lack of a true reference electrode means that only the cell potential is controlled, not the potential at the WE. Thus, if the potential at the CE is unstable and drifts over time, so too does the potential at the WE. However, the CE can serve as a pseudo-reference in a 2-electrode configuration so long as it can *efficiently* compensate the WE charge with minimal potential drift.

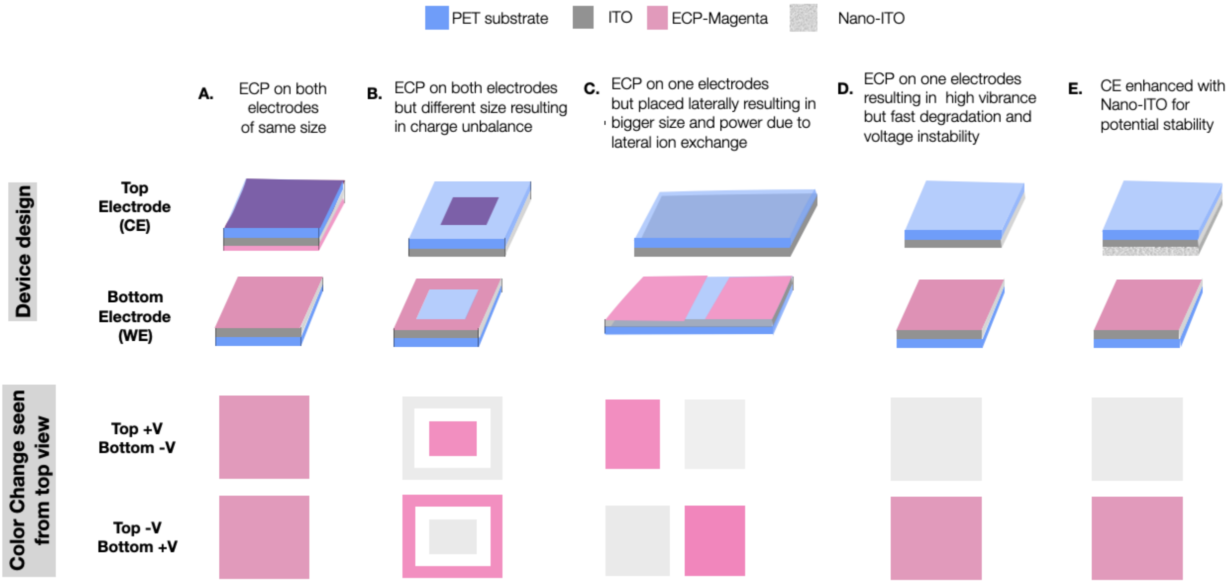
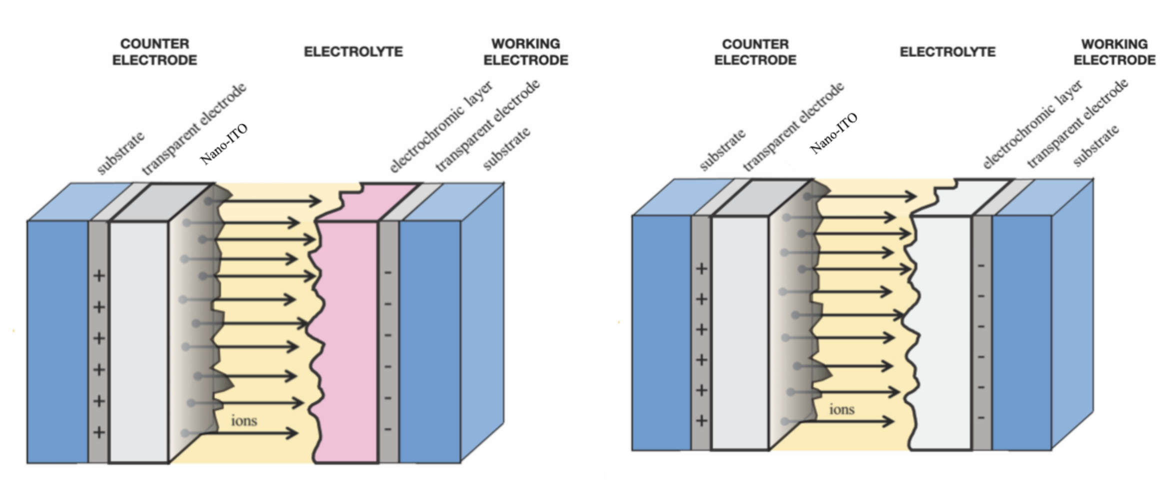


Figure 5.4: Different stages of CE design leads to charge-balanced optically-transparent counter electrode

For this, different strategies have been adopted. Figure 5.6a shows the use of another/same EC material as WE (Bottom) as CE (Top). This strategy often lacks the vibrancy of color in the device as both the +/- V application results in no color change if the same EC material is used [164]. There is also work done where Figure 5.6b CE is deposited with EC material to be a counter-image of WE electrode so that they both alternatively show color. The WE is clear when the CE is colored, and the WE is colored when CE is clear [89]. It often results in charge unbalancing between WE and CE due to differences in areas resulting in poor device performance. Thus, to maintain vibrancy and charge balancing together, ECD design with the horizontal placement of CE and WE laterally next to each other has been explored (Figure 5.6c) [9]. Since the horizontal alternative takes a large size, vertical ECD with transparent electrodes has been explored for high color vibrancy (Figure 5.6d) [164]. The CE is typically made of a transparent conductive material such as ITO due to its favorable optical properties. While this device functionally works with vibrant color changes from colored to clear, it has low stability. ITO is a poor charge-storage material and, thus, a non-ideal counter-electrode from an electrochemical point of view. Within a few cycles, it results in overall device performance degradation mainly due to the fouling of the ITO glass on CE as a result of gel electrolyte and ITO reductive decomposition.



Reduced **Oxidized**

Figure 5.5: Oxidation and reduction states of VENUS display with nano-ITO

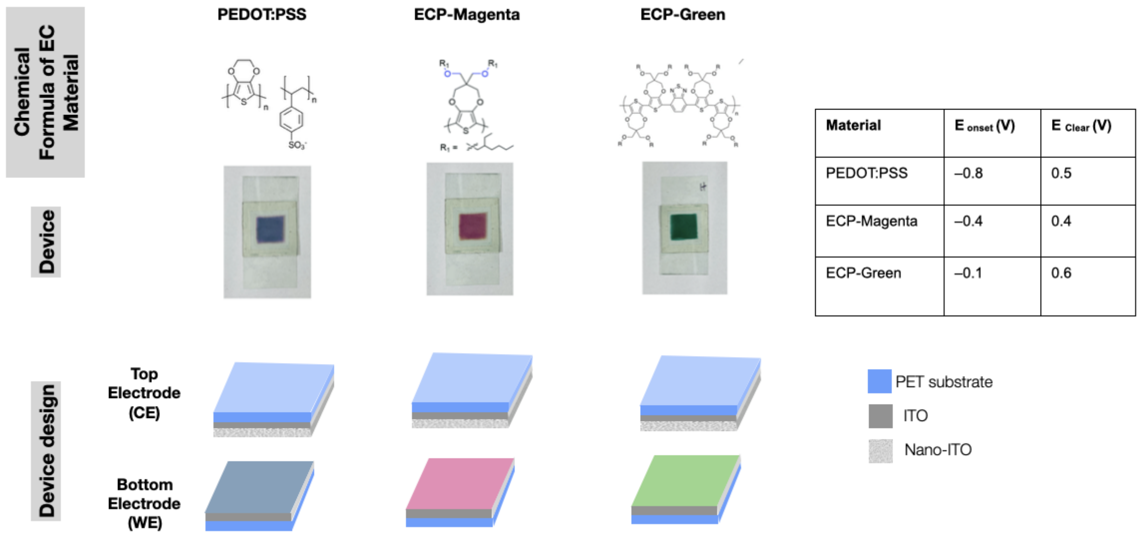
To overcome this **CE ITO degradation, the more efficient devices incorporate high-surface-area counter electrodes** with an extended number of electric double-layer sites, as opposed to just the standard ITO-coated glass electrode [4] (Figure 5.5). It allows for more stable electrode potentials even in the absence of a reference electrode and increases electrochemical cycling stability. Previous work has leveraged nanostructural metal oxide like, but they all have high-temperature annealing step and is sensitive to thickness changes [188]. To push for simple fabrication while achieving the design constraints of vibrancy, low-voltage, and low power with simple fabrication, I use mesoporous indium-tin-oxide (nano-ITO) coated on standard ITO glass as a non-polarizable counter electrode material for the VENUS EC display.

Nano-ITO serves as an optically and electrochemically inactive counter electrode and takes advantage of the electrochemical double-layer capacitance afforded by the high surface area of the nano-ITO (Figure 5.6e). The nano-ITO electrode has a sufficiently large surface area that the charge capacity is high enough (i.e., the effective current density is low enough) to counterbalance the charge passed by the EC polymer layer without undergoing electrochemical oxidation or reduction during device operation. Nano-ITO is easy to solution process and easy to deposit at low temperatures. This results in an ECD device that is vibrant in color change at low voltage/power but also thin and easy to fabricate by simple methods like blade coating. Next, we optimize the EC material for the CE-optimised device design.

Selection of ECP-Magenta Conjugate Polymer as Working Electrode for VENUS

The selection of working electrode's electrochromic material greatly dictates the voltage required for the redox reaction and, thus, the power at which the ECD device operates. Among these EC materials, conjugated polymers have shown high coloration efficiency, electron richness, fast response ($\sim$200 mS), and solution processability[165]. Conjugate polymers are basically alternating polymers based on repeat units of 3,4-ethylenedioxythiophene (EDOT), or 3,4-propylenedioxythiophene (ProDOT), in varying combinations that tune steric interactions and the subsequent optical absorption for fine color control.

I will be investigating three different types of conjugate polymers for their onset voltage (Colored reduced state) and clear voltage (colorless oxidized state) with the transparent



Material	E_{onset} (V)	E_{Clear} (V)
PEDOT:PSS	–0.8	0.5
ECP-Magenta	–0.4	0.4
ECP-Green	–0.1	0.6

Figure 5.6: Selection of ECP-Magenta conjugate polymer as working electrode based on Voltage of onset and clear

nano-ITO as the counter electrode and select the EC polymer to be used for the VENUS display. Each of these ECP has a transmittance of approximately 15% at λmax. They are

- **PEDOT: PSS [poly(3,4-propylenedioxythiophene)]** is a very commonly used conductive organic polymer in organic electronics as a p-type donor material. It turns clear on the application of E_{clear} voltage (0.5V) and darker blue on the application of E_{onset} (-0.8V). By default, it is in a light blue state.

- **ECP-Magenta** is a type of soluble all donor, electron-rich, pi-conjugated polymer that has ProDOT as its fundamental building block, which is substituted with 2-ethylhexyloxy solubilizing side chains that makes it solution-processable EC material. It turns clear at 0.4V and dark pink at -0.4 V.

- **ECP-Green** is also a type of ProDot polymer with formula P(ProDOT2-BTD-ProDOT2), where it uses 2-Ethyl and 2-EthylHexyl with the PE and shows green to clear transition on voltage application. It is green by default, turning clear at 0.6 V, and a darker shade of green with the application of -0.1V.

Given the ECP-Magenta has the lowest clear voltage and produces a maximum vibrant color change in the lowest voltage moving forward, we would be using it for the VENUS display. See section 5.5 for more details.

5.4 Fabrication: Materials and Process

The fabrication of the VENUS display is done in three steps. First is the preparation of the counter electrode. Second the preparation of the working electrode, and the final assembly of the two with the help of a separator where the electrolyte is contained. I explain the steps below:

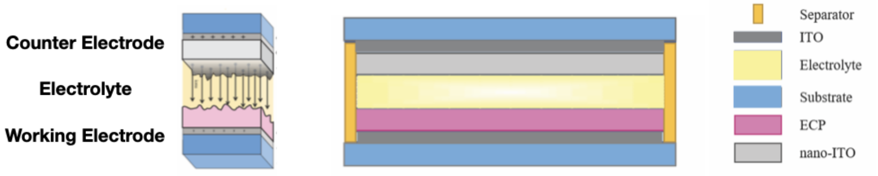
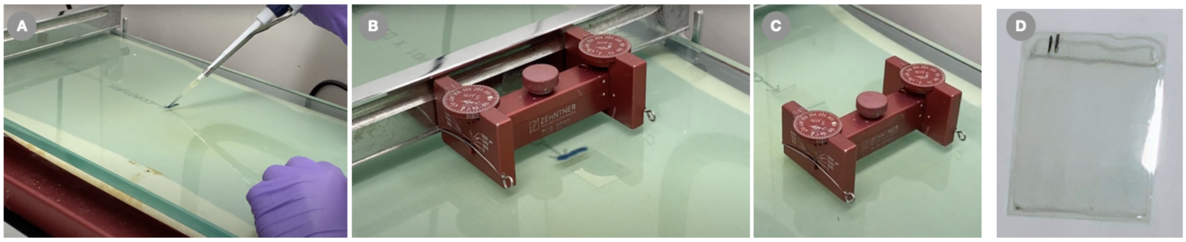


Figure 5.7: Device design crosssection with CE, WE, electrolyte, and separator

5.4.1 Preparation of Counter Electrode: Blade Coating of Nano-ITO



ITO coated PET is placed on blade coater and a line of nano-ITO is pipetted

Blade coater is run over the sheet

Evenly coated nano-ITO sheet is dried at 75 °C in oven overnight

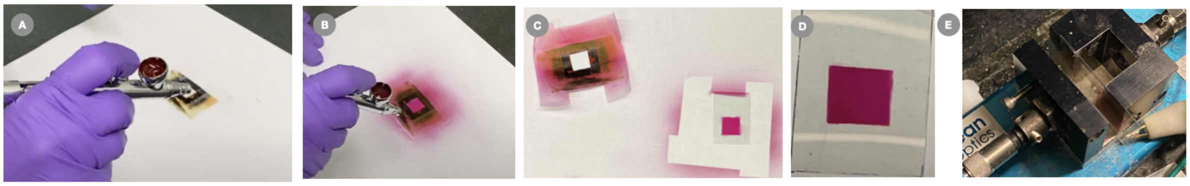
Transparent Counter Electrode (CE)

Figure 5.8: Preparation of the counter electrode

Polyethylene terephthalate (PET) (blue in Figure 5.7) precoated with indium tin oxide (ITO) (dark grey in Figure 5.7) purchased from YNvsibile is used as substrate. The sheets are cut into appropriate rectangular squares and placed on a blade coater with a conductive side facing upward. 30 microL of solution-processed Indium tin oxide nanoparticles (NPs) with a diameter of 50 nm (ITO-50) purchased from MilliporeSigma is poured using a pipette onto the sheet (Figure 5.8a). The blade coater set to 300um thickness of run over the sheet at speed 30, to obtain a thin shiny coating of nano-ITO (Figure 5.8b). The nano-ITO coated ITO/PET sheet is then placed oven at 75-80 degrees C for 72 hours to dry the nano-ITO to obtain the transparent counter electrode (Figure 5.8 c,d).

5.4.2 Preparation of Working Electrode: Air Spray of ECP Magenta

First, a mask is placed onto ITO/PET substrate sheet, and a 4 mg/mL toluene-based ECP-Magenta polymer ink is air-spayed onto the sheet using an airbrush with an argon pressure of approximately 20 psi (Figure 5.9). Next, the mask was removed, and optical absorbance spectra of the ICP-magenta sprayed into thin films were acquired using an Agilent Cary 5000 UV-Vis-NIR spectrophotometer scanning from 300-1600 nm by placing the sheet between two holders. The optical density of 0.8/transmittance of approximately 15% at λ max is measured using the spectrometer.



ECP-Magenta is filled in the air gun

Mask is placed over ITO coated PET and ECP-magenta is sprayed

Mask (left) removed to reveal ECP-Magenta coated PET (right)

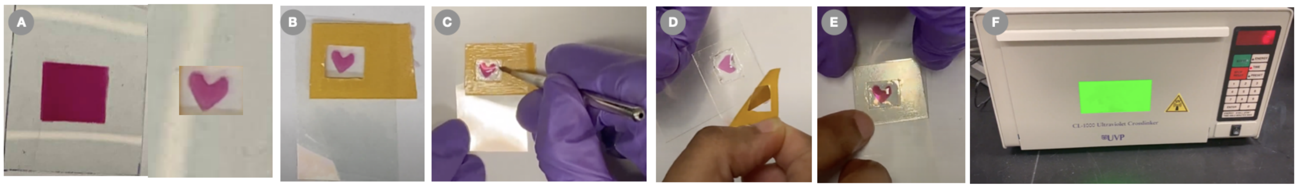
Working Electrode (WE) with ECP-Magenta

Spectrometer

Figure 5.9: Preparation of the working electrode

5.4.3 Device Assembly

After fabricating the CE and WE electrodes, I assemble them together. First, the working electrode with EC material is cleaned using a q-tip with IPA as required into a specific shape (Figure 5.10a). Next, an adhesive spacer (similar to double-sided tape) is cut in the shape of a frame to fit the edges of the display, and it is placed on top of the ITO/PET sheet coated with the ECP (Figure 5.10b). An adequate volume of Li+ electrolyte gel is applied inside the spacer frame and spread evenly using a brush (Figure 5.10c). The UV-curable electrolyte gel used is supplied by Ynvisible Interactive Inc. The adhesive tap on another side of the separator is peeled off (Figure 5.10d), and the counter electrode is placed with the nano-ITO side down onto the ECP-coated ITO/PET. Effectively the two PET sheets are arranged with the electrolyte gel sandwiched in between (Figure 5.10e). Finally, the device is placed in a UV chamber for 30 seconds (365 nm) to cure the electrolyte gel, the final composition of the ECD is shown in (Figure 5.10f).



ECP-magenta coated PET is cleaned with IPA dipped Q-tip coated to make desired shape

PET Separator as double sided tape is applied

Electrolyte is applied with a brush on top of WE

PET Separator tape is removed

CE is placed on top of Separator and pressed

The device built is cured with UV rays

Figure 5.10: VENUS display's device assembly

5.5 Working: 3 Modes of Operation - Clear, Off, Onset

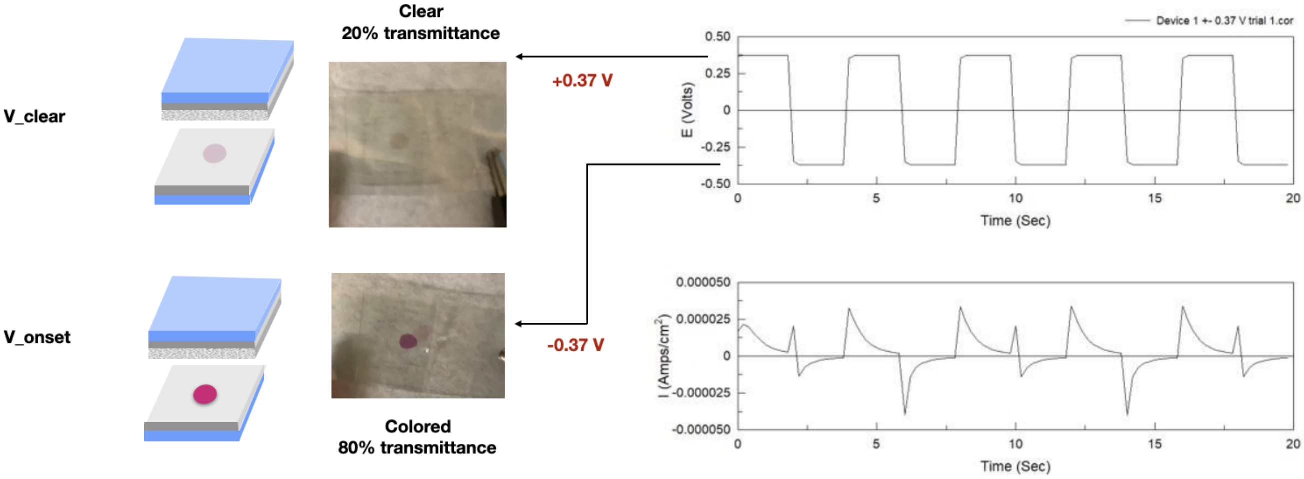


Figure 5.11: Shift of VENUS display from clear mode to onset mode with application +/- V square pulse voltage

Given the transparent counter electrode, the overall color of the VENUS display is controlled by the working electrode's optical color, which in turn is governed by the voltage being applied. Based on the theory of electrochromism discussed before in section 5.2 the *device shows the three different colors and thus 3 modes of operation with three different voltage application:* V_{clear}, V_{off} *(0V) and* V_{onset}.

The VENUS display ($8mm^2$) was switched with various pulse lengths of different voltages by using a EG&G PAR273 potentiostat/galvanostat controlled by the Corrware software. Increasing voltage potential is applied to VENUS display to find V_{clear} at 0.37V with a transmittance of 20% after which there is no significant visual change in color (Figure 5.11).Voltage in the opposite direction (V_{onset} of -0.37V) results in the colored mode with a transmittance of 80%. We repeated the same experiment for V_{clear} and V_{off} at 0V, which also shows the change in color or transmittance 60%, where devices change color from light pink to clear (Figure 5.12). In general, V_{clear} is a function of the internal resistance and capacitance of the device that changes with the size of the device, electrolyte, and EC material.

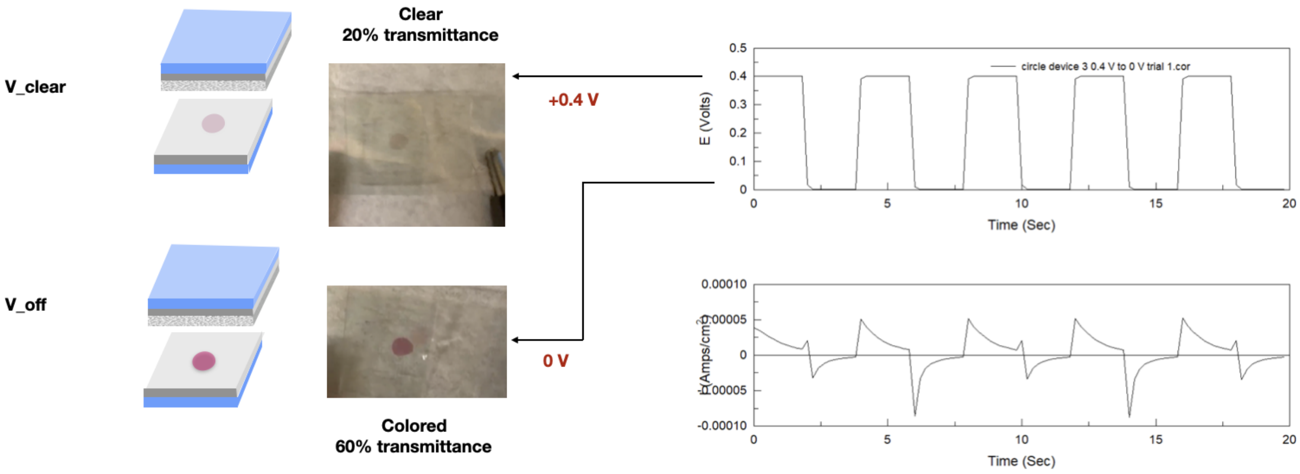


Figure 5.12: Shift of VENUS display from clear mode to off mode with application +/0 Volt square pulse voltage

Defining 3 modes versus 2 traditional modes of operation: Most research and applications of ECD consider only completely oxidized/clear mode and reduced/onset mode because of the high color contrast during device operation. It is important to note that to implement a feedback indicator it is not necessary to obtain maximum transmittance, but just a reasonable one. *In employing VENUS display, control circuits, and applications, I will also consider the off mode with* V_{off}*, 0 volt as it also has significantly different color change when compared to a colorless state. This significantly optimizes the power but also simplifies the control circuitry design constraints.*

5.6 Types of Information Conveyed by VENUS Display

VENUS display is capable of providing different types of information to the user as described below:

5.6.1 Color

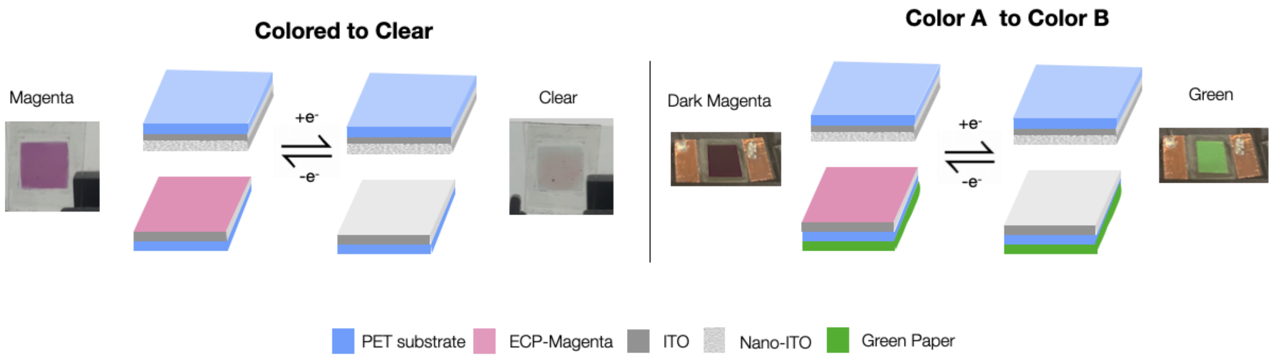


Figure 5.13: Magenta to a clear change in VENUS display can be modified to magenta to color X (e.g. green), by augmenting it with paper of color X.

Colors inherently have meanings/emotions attached to them. For example, red is considered a symbol for stop, and green is considered associated with go. The VENUS display inherently goes from pink/magenta color to clear. We can take advantage of the clear state to make the VENUS display go from magenta to any other color. The display can be further augmented with a paper strip of that color below the working electrode. For example, Figure 5.13 shows color changes from initial magenta to colorless and then after the addition of a green paper strip, it changes from dark magenta to green.

5.6.2 Shape

Shapes of different types are a powerful way to convey information. The working electrode can be etched into different shapes or emojis to convey meaning. For example, a heart shape conveys love and strategically is powered to create meaningful sustainable interaction (Figure 5.14).

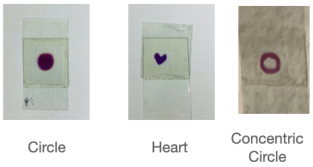


Figure 5.14: Different shapes can be etched out in the working electrode

5.6.3 Size

The size of the VENUS display is a critical factor that determines the power that will be consumed by the display to switch from one mode to another. Size informs the amount of EC materials on the working electrode that will undergo redox reaction and the ions stored at the counter electrode. It also determines the internal resistances and capacitances of the device. All these factors influence the ease of voltage and the mean power consumption for clear mode. EG&G PAR273 potentiostat/galvanostat controlled by the Corrware software to the voltage and current measurements.

We find the V_{clear} and I_{clear} of the square pulse for which VENUS display turns from transparent to colored (delta ~60% transmittance). See Figure 5.15. The lowest power is achieved by 3.14 mm^2 display which consumes 0.25 V and 20 μA, which is a 5 μW peak power pulse for clarity. Next is a 20 mm^2 device that consumes 30 μW while a 50 mm^2 consumes 480μW peak power. Such devices can be reasonably used to produce different

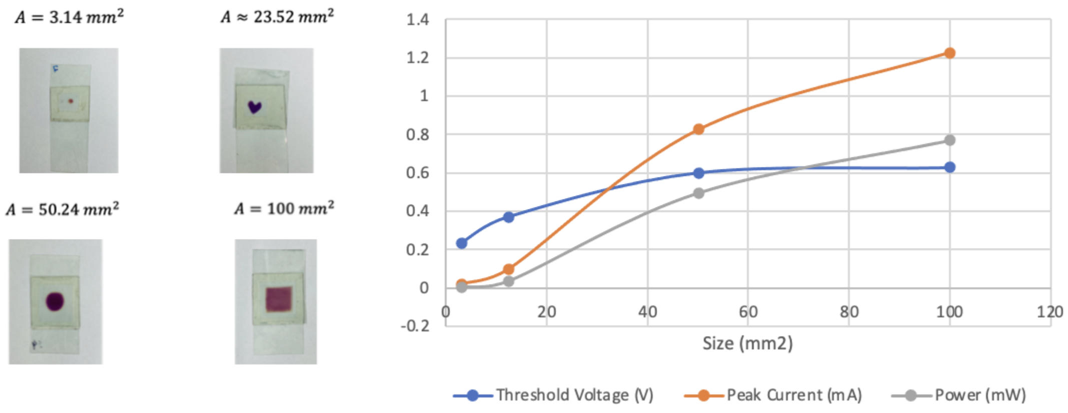


Figure 5.15: Effect of increasing size on VENUS display

types of small info-graphs. Finally, a 100 mm^2 device requires 0.6V at 1mA, which is 600 μW peak power. It can be used for more complex and big infographics.

Increasing the size increases both voltage and current, and thus the power. Specifically looking at the trend for voltage, it rises slightly from a device that is $3mm^2$ to $100mm^2$, but it more or less remains near the redox potential of the ECP-Magenta, which is $\sim$ 0.5 V. The current has a more sharp rise where it rises from 20μA to 1 mA. Size governs the peak power and voltage required, and thus it dictates which device is feasible to be operated self-sustainably or not. I will be looking at different types of power harvesting and ways of powering devices of different sizes.

5.7 Power Harvesting Strategies for VENUS Display

Previously to create sustainable interactive stickers we have pushed for an overall simple circuitry. I will maintain the same design parameters for the VENUS display as well as strategies for power harvesting techniques that fit with VENUS display with minimal power management circuitry. I will specifically leverage the fact that VENUS display's V_{clear} is orders of magnitude lower than traditional displays, which means it can be easily impedance matched with power harvesters as explored below:

5.7.1 Ambient Light

Traditionally ambient light can be harvested using a photodiode, which is a p-n junction that produces current when it absorbs photons. As explored in MARS (chapter 4) before, in ambient room light (300 lux), a single photodiode provides 250 mV and $1.5\mu A$ DC power. Thus, given the VENUS display consumes ∼400 mV of V_{clear} startup voltage, we can arrange two photodiodes in series to add up voltages to create more than sufficient power source for the ECD display to turn from off mode (light pink at 0V) to clear (Figure 5.16). This setup with a switch can reasonably operate the VENUS display of $< 25\ mm^2$. For bigger sizes, more photodiodes can be added in series.

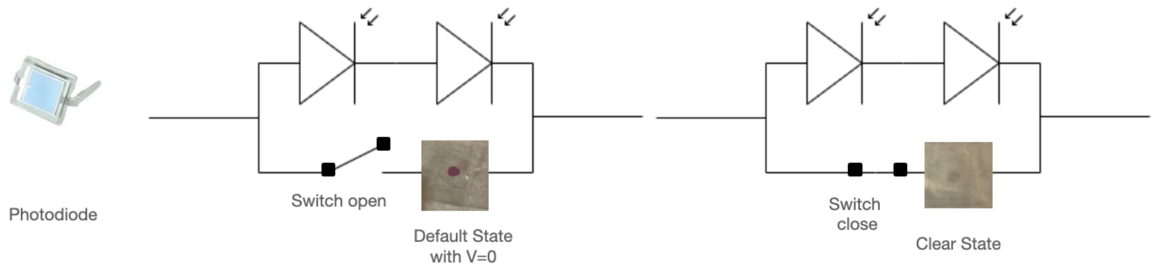


Figure 5.16: Few photodiodes connected in series can produce enough DC power to change the VENUS display from default to clear operational mode in ambient room light

5.7.2 Finger or Hand Heat

A thermoelectric generator (TEG) can transform thermal energy directly into electric energy through the thermoelectric effect. Figure 5.17 shows the general structure of a TEG. It consists of a heat exchanger, a thermoelectric module (TEM), and a heat sink. The hot side absorbs the heat and transfers it to the TEM, which typically contains a number of pairs of p- and n-type semiconductors connected electrically in series and thermally in parallel. Charge carriers are electrons in doped n-type semiconductors, and holes in doped p-type semiconductors. The cold side dissipates the additional heat from the TEM. A TEG is able to transform the temperature difference into electrical energy through the Seebeck effect. If one side of the TEM is hotter than the other, the electrons on the hot side have more kinetic energy than those on the cold side. Therefore, the electrons travel faster from the hot side to the cold side, such that the charge carriers diffuse away from the hot side which leads to a buildup of charge carriers at one side as shown in Figure 5.17. The hot side of the TEM will eventually be positively charged while the cold side is negatively charged. This buildup of charge creates a voltage potential that can be superimposed with the increasing number of pairs of p- and n-type semiconductors. Conversely, touching the TEG module on the other side results in the cold and hot sides being exchanged producing opposite potential. Figure 5.17 demonstrates that touching side 1 of the TEG module results in a negative potential across the load and touching side 2 with the hand results in positive voltage. It is similar to the square pulse generation with which we tested the VENUS display. Since VENUS displays have a low startup voltage they can be impedance matched with a TEG without additional voltage regulators or doublers.

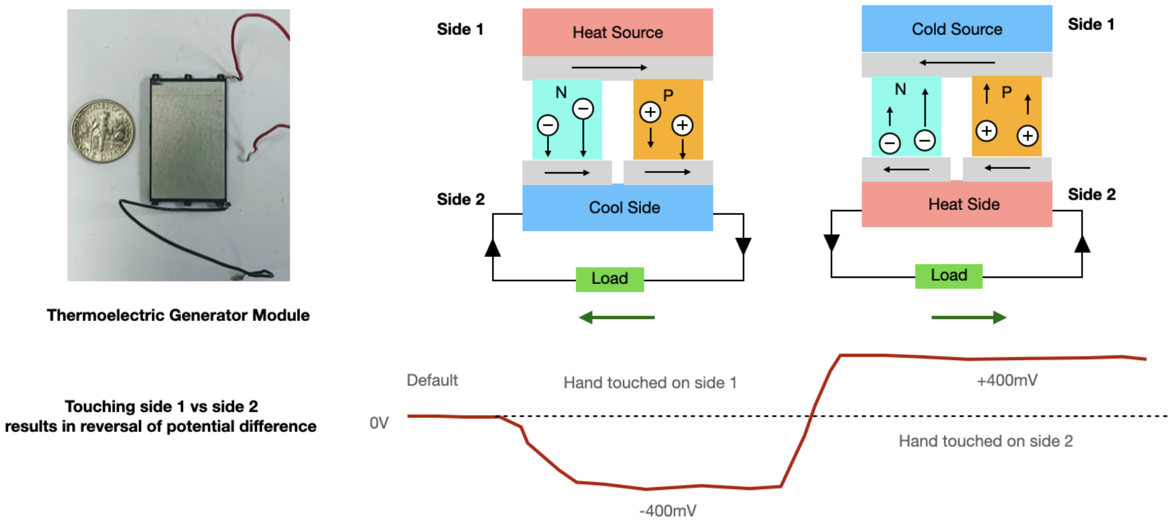
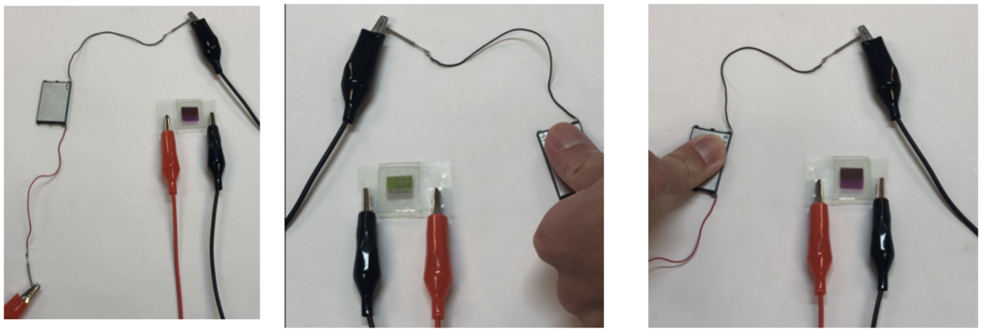


Figure 5.17: Touching TEG module with hand on side 1 produces negative potential and on side 2 produces positive potential. It is similar to the square pulse produced during to testing (Figure 5.11) to control VENUS display to go from onset mode to clear mode.

5.8 Designing Interactions Based on the Type of Power Harvester

Next, I design interactions for controlling the VENUS display that exploits our understanding of how harvesters like photo-diodes or thermoelectric generators work to produce DC potential.

5.8.1 Thermoelectric Based Touch Interaction: Clear to Onset Mode


Off Mode
TEG module at room temperature
V_off=0

Clear Mode : +V
Touching on one side results in
revealing green indicator paper

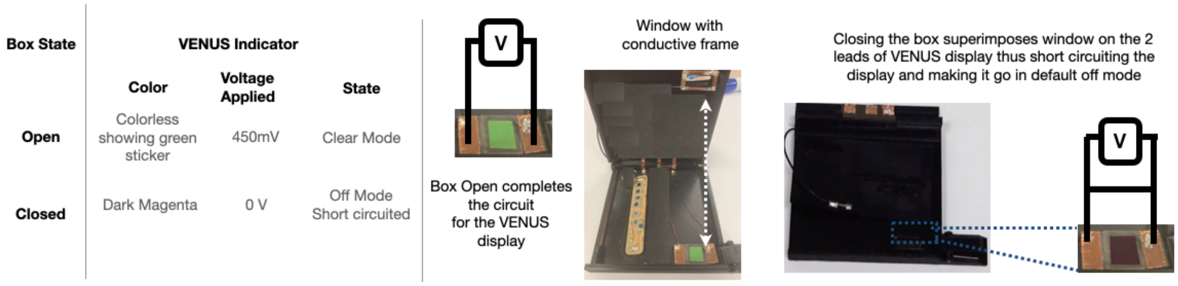
Onset Mode : -V
Touching on opposite side results
in changing the state back to pink

Figure 5.18: Hand-powered control of VENUS display's different modes of operation

The direction of the current generated by the Thermoelectric Generator (TEG) depends on the heating side, which is opposite to the direction of the electron flow in the TEG. Exploiting this phenomenon, a novel interaction between the TEG and the VENUS is designed. When the user touches one side of TEG with their finger as the heating side, VENUS ($100mm^2$) will display color 1 (e.g., magenta) while flipping the TEG and touching the other side, VENUS will display color 2 (e.g., green in the clear state) (Figure 5.18). In addition to changing the applied voltage by flipping the TEG, two TEGs of opposite polarity placed connected in parallel can also be used to control the color change of the VENUS display.

5.8.2 Ambient Light Powered Opening/Closing Box Interaction: Clear to Off Mode

In subsection 5.7.1 I demonstrated how the DC voltage of the photo-diode can be used to power a display, and the switch required to control the shift between the clear to default Off state. Here we describe how opening and closing a box can be synced as a switch for the VENUS display. A box with a window is created in such a way that the VENUS display



Box State	VENUS Indicator		
	Color	Voltage Applied	State
Open	Colorless showing green sticker	450mV	Clear Mode
Closed	Dark Magenta	0 V	Off Mode Short circuited

Figure 5.19: Box with conductive frame window: When the box is open the VENUS display is in a clear state with a green indicator. In the closed state, it turns to the default state due to short-circuiting and discharge of charge by the window frame

is placed exactly in alignment with the window if the box was closed. The window has a protruding frame that is made conductive with copper tape Figure 5.19.

When the box is open, the light on the photodiode placed inside the box produces voltage enough to make the VENUS display go into clear mode, thus revealing the green paper below. When the box is closed, there are two features are work together to make the VENUS display go to default colored mode. First, the photo-diode stops producing voltage to the display, but this is not enough since ECD has a memory effect due to which it acts as a super-capacitor. To discharge this super-capacitor, we leverage the second feature, which is the conductive window. When the box is closed the conductive window frame touches the two electrodes of the VENUS display, causing a short and discharging of the display. Thus, we have created a box design that controls switching on/off indicators with its opening and closing.

5.9 Exploration of Application Space

Based on the device design, power harvesting strategies and interactions designed, I will explore some potential applications for the VENUS display.

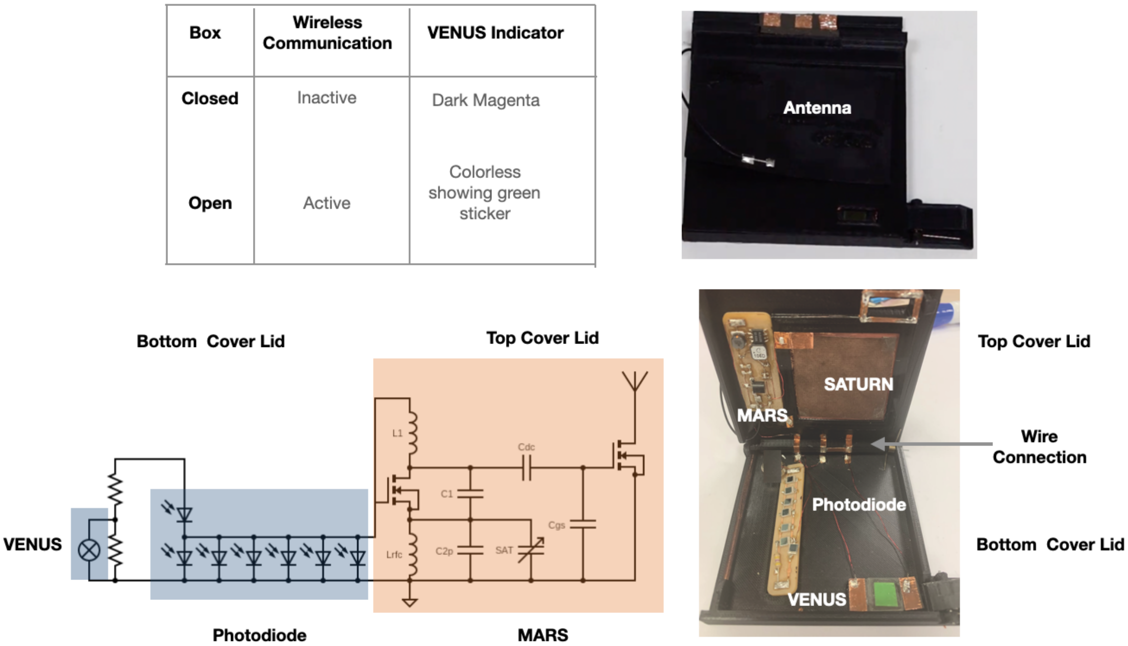
Figure 5.20: Hand touch powered interactive cards a. TEG connected to VENUS display embedded in card b.VENUS display in onset and clear mode c. Interactions that change the state of VENUS display with respect to card

5.9.1 Finger Heat Powered Interactive Cards

The VENUS display can be used to augment interactive children's books or greeting cards. Figure 5.20 shows a heart-shaped VENUS display embedded with leads directly connected to a TEG. In the default state, it is magenta in color, but based on the text of the card, the self-powered playful interactions can be designed with a thermoelectric generator, which changes the state of the VENUS display info-graphic from clear to default and back.

5.9.2 Addition of On/Off Indicator to Wireless Audio Communication Sticker

In MARS (Multi-channel Ambiently-powered Realtime Sensing), I demonstrated examples of nano-power battery-free wireless interfaces for touch, swipe, and speech input (chapter 4). One of the current limitations of MARS is that users do not receive feedback from their interaction with MARS. Without proper feedback, users have no ability to know whether MARS has responded to their input, resulting in a lack of usability for an interaction-sensing device. Adding a display requires being cognizant of the power requirements and restricting them to ∼10 µW for it to be self-sustainable while maintaining the form factor and cost of power circuitry. VENUS, with its low power consumption and simple fabrication, makes it the ideal candidate for MARS onboard displays. Thus, the addition of a VENUS as an on/off indicator in a MARS allows for potentially improved usability and privacy.



Box	Wireless Communication	VENUS Indicator
Closed	Inactive	Dark Magenta
Open	Active	Colorless showing green sticker

Figure 5.21: Employing VENUS as an on/off indicator for wireless communication. In the box closed state, the VENUS display is in off or discharged mode, and MARS is not communicating. In the box open state, the VENUS display is in ON in clear mode, and MARS is communicating

Figure 5.21 shows the prototype of a box where MARS circuitry is placed. The MARS oscillator, SATURN, and antenna are placed on the top lid cover that opens up (marked in orange in the circuit diagram), and the photodiode and VENUS display is placed at the bottom cover lid (marked in blue in the circuit diagram). The photodiodes are arranged in such a way that in the presence of light, they produce enough power to light up both VENUS and MARS. Two photodiodes are in series with a current limiting resistor to be able to operate VENUS $\sim$ 400 mV startup voltage, and five other photodiodes are in parallel to power up the MARS circuitry $\sim$ 200 mV. The arrangement of photodiodes in this way prevents the mismatch of operating voltage between VENUS and the rest of the circuitry, as well as saves power management circuitry costs.

When the box is closed, the photodiodes do not produce enough power for MARS circuitry to operate, and the VENUS display is in discharged Off state. It means that its wireless communication is inactive, and the indicator is also in-sync with the state. In addition, there is a physical disconnection that happens between the top and the bottom cover on opening and closing of the cover as means for additional usable privacy features. When the box is open, the physical connection between the top and bottom cover is completed, which leads to power from the photodiodes being supplied to MARS circuitry and SATURN for active communication. The power from the photodiodes also turns the VENUS display clear, thus green, due to the addition of green paper at the bottom. Thus, box opening and closing controls on/off of MARS wireless communication and VENUS display.

5.10 Discussion: Limitations and Future work

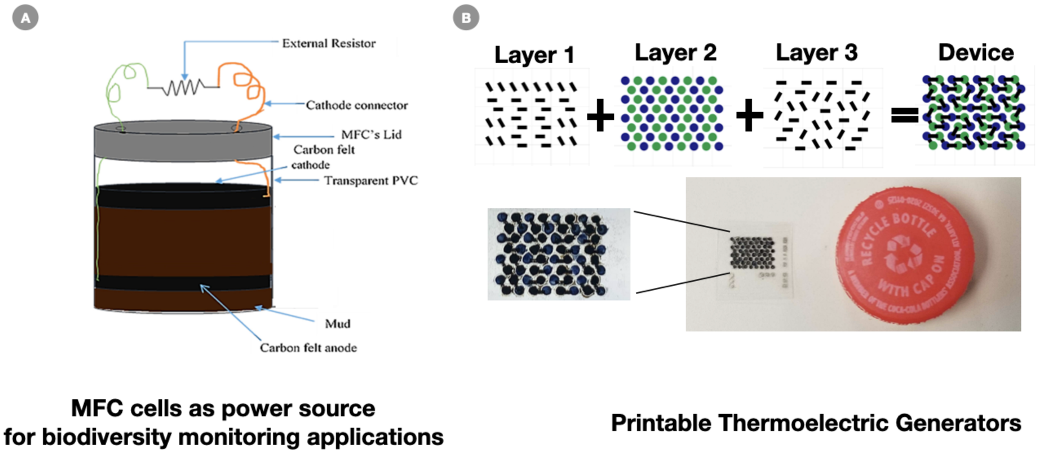
We have demonstrated the VENUS display to be an easily fabricated low-power and voltage alternative vibrant on/off feedback mechanism for low/self-powered systems. Below we discuss some limitations and future work where this work can be expanded:

5.10.1 Ways of Improving Device Lifetime

The devices demonstrated some degradation when left in normal bright room light for a number of weeks. It is probably due to the oxidation of electrolytes and lack of proper encapsulation. Thus, there is more work and device characterization to be done for the stability of the device over long periods in real-life practical scenarios.

5.10.2 Alternate Power Harvesting Strategies

Previously, I have explored photo-diode and thermoelectric generators as DC power sources and designed interactions for them to power the VENUS display and MARS wireless communication. One common thread between the power harvesters and the circuitry and systems built was the impedance matching without complex power management circuitry due to low-voltage operation. There are other types of DC power sources like microbial fuel cells that also fit the same category (Figure 5.22a). MFC produces hundreds of mV leveraging ubiquitously available soil and the bacterial communities in it. Exploring such alterna-



MFC cells as power source for biodiversity monitoring applications

Printable Thermoelectric Generators

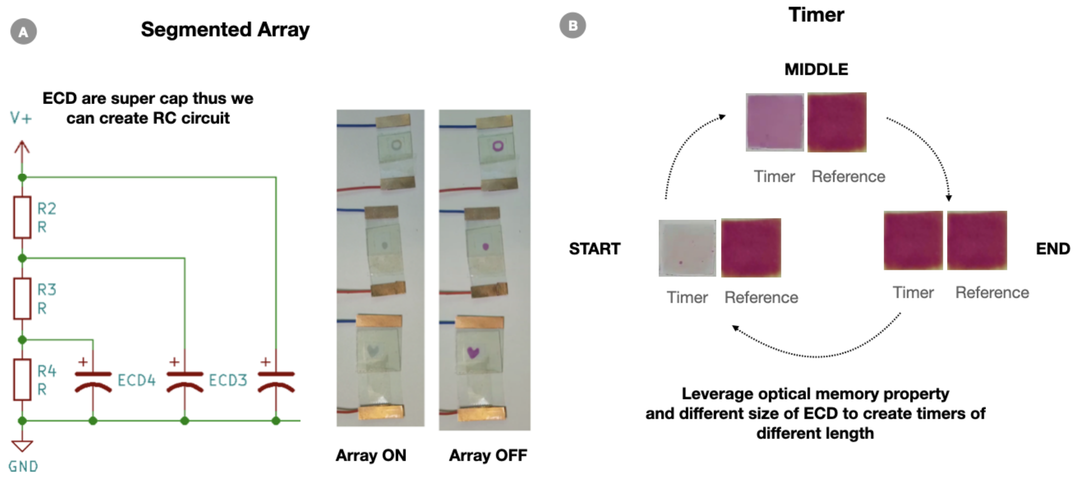
Figure 5.22: Alternate DC power sources to explore

tive power sources opens doors for sustainable self-powered wireless sensing and feedback applications in infrastructure monitoring, smart farming, and sensing for conservation. Additionally, these DC power sources can be voltage multiplied using simple low-voltage and power colpitts oscillator circuit with zero-threshold voltage transistor as built for MARS. It leads to efficient power management with minimal silicon components.

In the future, printable flexible TEG can be fabricated to power VENUS instead of using a commercial bulky TEG. Such flexible TEG can conform to the body yet ensures efficient heat transfer. Figure 5.22b demonstrates how such TEG devices can be built by compactly printing p-n type materials together [44].

5.10.3 Explore other self-powered circuit systems with VENUS

The VENUS display is low-voltage and power and acts as a capacitor when uncharged and as a short circuit when charged. Due to these unique properties, we can leverage them to create a segmented display that switches on sequentially as the voltage supplied increases. Figure 5.23a shows a circuit with 3 VENUS displays as capacitors in parallel to each other with resistances that act as a voltage divider. The resistor values can be chosen in such a way that we attain sequential switching on behavior. The R values will be constrained under two parameters: (1) the time to charge/discharge an ECD and (2) the total power consumption of the display. If the resistor values are very large, the total power consumption of the display falls dramatically. However, due to the low current capacity of the resistors, the ECD's would struggle to turn on / off quickly enough to be practical. If the resistor values are very small, the ECD's respond quickly, but the total power consumption of the display ends beyond the capabilities of the energy harvesting. With the creation of the right RC circuit, we can create level indicators.



ECD are super cap thus we can create RC circuit

Leverage optical memory property and different size of ECD to create timers of different length

Figure 5.23: a) VENUS Arrays as level indicator b)Exploit memory effect of VENUS display for creating self-powered timers

ECDs act as super-capacitors, which means that once they go from default off to clear mode or default off to onset/colored mode, they do not immediately come back to the default mode and slowly discharge. The charge stored shows up as optical memory. This effect can be leveraged to produce visual timers. More work can be done to create systems with appropriately characterized power sources and VENUS displays to create timers of different duration. For example, a VENUS display of size 1x1 cm^2 can keep charge saved for a few hours.

This three-state memory behavior of VENUS can also be used to create optical memory digital readouts for non-interactive computing elements. That is, in intermittent computing systems, VENUS can help communicate the charge stored in the storage capacitor.

5.11 Conclusion

In this chapter, I first introduce the VENUS display, an electrochromic device design that allows for low-voltage operation and vibrant colors. I further showcase how VENUS can be fabricated using simple techniques and its different modes of working. Next, I explore ambient light and finger heat as ways of powering VENUS and design interactions that control power input in sync with different modes of operation. I leverage this to elucidate potential applications of VENUS as a low-power on/off indicator for sustainable interactive objects and stickers.