



VIM: Customizable, Decomposable Electrical Energy Storage

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Figure 1: Readily fabricated in a makerspace, VIMs can take a variety of shapes and form factors.

ABSTRACT

Providing electrical power is essential for nearly all interactive technologies, yet it often remains an afterthought. Some designs handwave power altogether as an “exercise for later.” Others hastily string together batteries to meet the system’s electrical requirements, enclosing them in whatever box fits. VIM is a new approach – it elevates power as a first-class design element; it frees power from being a series of discrete elements, instead catering to exact requirements; it enables power to take on new, flexible forms; it is fabricated using low-cost, accessible materials and technologies; finally, it advances sustainability by being rechargeable, non-toxic, edible, and compostable. VIMs are decomposable battery alternatives that rapidly charge and can power small applications for hours. We present VIMs, detail their characteristics, offer design guidelines for their fabrication, and explore their use in applications spanning prototyping, fashion, and food, including novel systems that are entirely decomposable and edible.

CCS CONCEPTS

- Human-centered computing → Interactive systems and tools.

KEYWORDS

sustainability, biodegradation, decomposable materials, energy, supercapacitors, DIY



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CHI '23, April 23–28, 2023, Hamburg, Germany

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ACM ISBN 978-1-4503-9421-5/23/04.

<https://doi.org/10.1145/3544548.3581110>

ACM Reference Format:

Katherine W. Song and Eric Paulos. 2023. VIM: Customizable, Decomposable Electrical Energy Storage. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23), April 23–28, 2023, Hamburg, Germany*. ACM, New York, NY, USA, 18 pages. <https://doi.org/10.1145/3544548.3581110>

1 INTRODUCTION

There is a great disconnect between the design of portable interactive electronics and the design of the energy storage systems that power them. Consider the following: Alice is a designer who wishes to create a small interactive electronic ring to wear for a few hours at an upcoming special event. She begins by prototyping on a benchtop, using a power supply to power her electronics and focusing on refining her desired interactions and aesthetic elements, which she can iteratively prototype quickly. Once satisfied, Alice makes the appropriate electrical measurements to estimate the power consumption of her system. The system turns out to be very low power, requiring only 1V and consuming at most 1mA. Looking through an online catalogue, Alice finds that the smallest battery that can suit her needs is a 3.7V, 110mAh lithium ion battery that costs \$6 (USD)¹. It will arrive in 2-5 days. While the battery is relatively small – half the size of a thumb – it is still large for Alice’s on-finger application and will power the system almost 100 times longer than necessary. Alice is further disappointed to realize that after the event, she will have no use for the battery, and it will simply sit in her drawer and gather dust alongside her growing collection of old batteries. While waiting for the battery to arrive, Alice adjusts her design, increasing its size substantially to accommodate, hide, and protect the battery.

Although this is a hypothetical scenario, we believe that it is a relatable one that illustrates the dissonance that arises when making a design that is intended to be portable actually portable. For electronics prototypers, makers, and hobbyists, power is often a mere afterthought that is designed around late in the design process.

¹<https://www.sparkfun.com/products/13853>

At that point, a designer may find themselves constrained by the limited, discretized options that exist commercially. Off-the-shelf batteries, the most common form of energy storage for portable electronics, can be cumbersome to work around. Without expensive customization, they are limited in form factor options, existing as cylinders or blocks that are almost always rigid. They can be bulky eyesores, especially when multiple units are haphazardly strung together, posing a thorn for the aesthetics or wearability of a design. It is no wonder that the batteries or bulky power supplies behind the scenes in research prototypes of many impressive interactive technologies are often only very fleetingly mentioned in papers or are sometimes left out of the discussion and figures entirely.

Some systems have been designed to avoid energy storage altogether, harvesting small amounts of energy from the environment to directly power ultra-low-power systems [4–6]. Still others avoid energy storage by utilizing near-field wireless power transfer from wireless chargers [97] and mobile devices [29, 30, 43]. Nonetheless, on-board energy storage is unavoidable for several interactive systems that require more power than can be continuously harvested ambiently (i.e. $>1\text{mW}$) or that need to operate in situations where wireless power transfer is unavailable or inconvenient. Unfortunately, the industry goals of developing batteries that endure for as long as possible are often not aligned with the needs of small-scale designs. Conventional lithium ion batteries are well suited for phones, laptops, and other power-intensive devices. However, for other lower-power or temporary interactive systems – both existing and yet to be developed – using such high-capacity batteries is arguably excessive. These are the applications that we target in this paper. In this domain, we can free ourselves of the constraints of performance optimization and capacity maximization, instead experimenting with more accessible, low-cost, non-toxic, and customizable materials that designers can use to draft their own energy storage modules that cater exactly to their needs.

Addressing the current inability to customize energy storage for our designs is more than just a matter of enabling new aesthetic and functional possibilities. Batteries present a serious sustainability problem and are some of the most environmentally hazardous components of electronic interactive systems. They rely on toxic metals, such as cadmium, lead, or lithium, that are extracted through resource-intensive processes and must be carefully recycled or contained at end of life. Waste handling is a particularly troublesome challenge for not only individual designers but also electric car manufacturers and consumer electronics companies as they strive for more sustainable practices. Lithium ion batteries that are improperly disposed of in regular landfills can cause fires, endangering nearby communities [3]. The lack of sustainable energy storage alternatives is a substantial obstacle in the path of the collective efforts among the Human-Computer Interaction (HCI) community of makers to create eco-friendly interactive systems [7, 9, 10, 58, 97, 108].

Rejecting the idea that energy storage remains an afterthought in the design process, we propose instead that it takes a front seat early on, alongside the other elements of an interactive system. Resonating with calls in the HCI community for more eco-friendly materials and design practices, we further insist that this be done by foregrounding sustainability and prioritizing materials that are biological, renewable, and *decomposable* – that is, easily degradable

without specialized industrial conditions. We seek to enable this by presenting VIMS²: fully decomposable energy storage elements that can be rapidly charged and recharged and that hold power for days. Cheap and safe enough to fabricate at home, VIMS are capable of powering interactive systems in applications spanning fashion, health, food, and more. VIMS, while low performance by industry standards, present three key advantages over commercially available energy storage for the HCI community. First, they are made with low-cost, accessible materials and technologies. Secondly, they are thin, conformable, and customizable in form factor, enabling a new degree of design flexibility when prototyping. Finally, they degrade under backyard conditions, greatly reducing the resource cost and complexity of disposal. This in turn enables new kinds of interactive electronics that are also completely decomposable. In the rest of this paper, we detail the following contributions:

- Adaptable, accessible guidelines for designing VIMS
- The detailed fabrication and characterization of an exemplar VIM
- Demonstrations and discussion that highlight the functionality and advantages of customizable, decomposable energy storage

2 RELATED WORK

This paper draws inspiration from a rich body of research in battery-free systems and materials for sustainable design. Here, we summarize prior work in these areas and describe how this paper is situated with respect to existing approaches.

2.1 Battery-Free Systems

One promising strategy for simultaneously side-stepping the energy storage problem and reducing electronic waste lies in the creation of self-sustaining and battery-free systems. Researchers have discovered methods to eliminate on-board batteries by engineering systems that can be powered wirelessly. Inductive chargers [72, 84, 97, 103] and near-field communication (NFC) [29, 30, 43, 109, 122] have been successfully used to wirelessly power interactive systems across small (centimeter-scale) gaps. Large-scale wireless chargers can be integrated into surfaces [101, 118] and even clothing worn on the body [102], extending the breadth of scenarios for which wireless power transfer is possible. Using ultrasound, the working range of wireless power transfer may be extended even farther; Gonzalez et al. successfully used ultrasound transmitters to power micromotors, buzzers, and LEDs from almost a meter away [75]. Still, in general, most schemes such as these are effective solutions only if wireless chargers, mobile devices, or other wireless power transmitters are nearby, which might not be the case in, for instance, remote or unmanned environments.

For some interactions, the act of bringing a device near a wireless power transmitter is unnatural or not always practical, and for these, researchers have developed alternate power schemes. There have been demonstrations of ultra-low-power ($<1\text{mW}$) systems that can communicate solely using the power from ambient RF, a mechanism called ambient backscatter [63]. Electromagnetic energy from TV signals [63, 79], WiFi [12, 124, 125], Bluetooth [125],

²The Oxford English Dictionary defines *vim* as: force or vigour, energy, ‘go’

and AM/FM radio [4–6, 110, 111] may be employed for such systems. Ambient backscatter has enabled self-sustaining, low-cost systems for the sensing and communication of audio and touch, and it has been integrated with other forms of energy harvesting as well. For example, Arora et al. presented a self-powered microphone that runs on a triboelectric nanogenerator harvesting energy from vibrations [6] and communicates using analog backscatter [4]. Zhang et al. presented *Sozu*, a system that harvests mechanical, thermal, solar, and electromagnetic energy to power an RF broadcast that can in turn be received by a remote device [126]. Hand cranking may also be used to power small systems [66]. Interactive Generator [8] used the manual rotation of a servomotor to generate power for various electronic interactions and also provide haptic feedback to the user. Hand cranking can generate more instantaneous power than nanogenerators can, but a downside for both is that without integrated energy storage, power is supplied for only as long as the cranking or other activity from which energy is harvested continues. For those applications that are low power enough to operate solely on ambient RF waves, which are reliably available in many locations around the world, this may not be a major concern, but other applications still require on-board energy storage to operate without interruption and as intended.

Our work adds yet another option to this increasingly rich pool of techniques and is especially attractive for the many applications that require more power than that which can be harvested from the environment continuously. After presenting the design, characterization, and example applications of VIMS, we also discuss the considerations involved in deciding if VIMS are indeed the most suitable option – both in terms of performance and environmental impact – for a given system.

2.2 Materials for Sustainable Design

We are by no means the first HCI researchers to call for more sustainable design and prototyping [14, 15, 31, 58, 69, 82]. Upcycling [20, 40], “salvage fabrication,” [28], “unmaking” [98], and fabrication with disassembly in mind [119] are just a few promoted practices that aim to reduce waste by supporting prolonged material use and reuse. Selecting the right materials in the first place is also an important component of sustainable design [58], and in that regard, there have been many exciting recent developments as well. For example, mycelium, the vegetative root structure of fungi, has been posed as a replacement for conventional plastics in many applications and boasts the benefits of being growable by an amateur maker, decomposable, moldable, and millable [51, 107, 108, 117]. Beyond mycelium, flax fiber and poly-vinyl alcohol (PVA) are other decomposable materials – dissolvable in water, in fact – that may be used as substrates and enclosure materials for electronics [7]. Food-grade bioplastics [9] and biomaterial made from compost [10], which can incorporate interactive elements such as photochromic or thermochromic inks, have also been demonstrated as viable materials for yet other eco-friendly designs.

Still, there remains much work to be done when it comes to making sustainable interactive electronics. While the aforementioned materials are decomposable, they are not electrically active. Thus, any added circuitry must be manually separated from their degradable substrates and enclosures if they are to be reused, and

once they have reached the end of their life, their disposal is still environmentally problematic. Researchers across multiple disciplines have been actively searching for new materials to make conventionally non-decomposable components more “green” [60]. Paper [17, 26, 85, 86, 106], chitin [47], and silk [105] have been successfully used as substrates and encapsulation materials. Additionally, researchers have reported the use of thin films of silver nanowires (Ag NWs) [42], carbon nanotubes [42], iron [123], magnesium [123], and conductive polymers such as poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) [59] to make conductive electrodes that readily biodegrade into non-toxic particles. Others have 3D printed conductive structures from salty food items like Vegemite and Marmite [39]. Conductive traces have even been made by lasering wood and other carbon-rich substrates with a de-focused laser cutter, creating graphene [25, 45]. In some cases, living organisms that change shape or color may be utilized in lieu of some electronic components [38, 50, 77, 80, 121]. Nonetheless, with very few exceptions [97], complete interactive systems with these material innovations still use non-decomposable wiring, batteries, microcontrollers, and/or substrates to varying degrees. Individual research papers often focus exclusively on developing green alternatives for one electronic component – or sometimes just a single material layer of a component – resulting in provocative findings but still leaving questions around the feasibility of fabricating fully decomposable systems unanswered.

As we subsequently discuss, VIMS are functionally supercapacitors – capacitive structures that store charge electrostatically. Supercapacitors are known for their ability to charge and discharge quickly and their prolonged lifetime in comparison to batteries, making them valuable for applications such as regenerative braking [81, 127]. Making eco-friendly supercapacitors is the subject of much research in materials science and traditional engineering disciplines [2, 13, 33, 41, 48, 61, 68, 120]. However, while these approaches replace at least one conventional layer with a natural material possessing a lower carbon footprint, they still utilize some expensive and toxic materials, such as nano-engineered materials and acrylamide [2, 41, 68, 120], or specialized processes, such as high-temperature heating under inert or vacuum conditions [13, 68, 120]. These cannot be simply ported into a makerspace or otherwise accessible fabrication environment. This is not to say that Do-It-Yourself (DIY) methods do not exist at all, however. In recent years, demonstrations of DIY supercapacitors have cropped up on online platforms, such as YouTube [21, 57, 76, 99], allowing hobbyists to begin to take more control over their energy storage designs with a simple web search. Potato slices, or even whole potatoes, can also be used as batteries when paired with copper and zinc electrodes [1, 37]. Although such designs do share a subset of materials with the VIMS that we present, like the aforementioned research papers, these DIY demonstrations still rely on non-decomposable components, such as steel or aluminum plates, plastic enclosures, copper wires, and metal nails. Additionally, they are often bulky and not adaptable to arbitrary surfaces, limiting their applications.

One notable demonstration of a decomposable supercapacitor made without exotic techniques or materials is a paper by Wang et al. in *Advanced Materials Technologies*. The authors reported supercapacitors made from food items that, when connected in series,

can power a small endoscopic camera for 10 minutes [113]. VIMS improve upon Wang's supercapacitors in terms of both performance – extending working time from minutes to hours and days – and design customizability. We offer accessible design principles that can be easily followed and adapted for widespread explorations, as well as a set of technical characterizations and design applications more relevant to the HCI community.

3 DESIGN OF VIMS

3.1 Operating Principles

VIMS are electrical double layer supercapacitors (EDLCs) that store energy at two layer interfaces within a multi-layer stack (Figure 2). To enable successful material experimentation within our design, it is necessary to first understand the basic operating principles of supercapacitors. A regular capacitor comprises two conductive electrodes separated by a solid insulator. In comparison, a supercapacitor comprises two conductive electrodes separated from one another by a liquid or gelatinous electrolyte that is abundant with mobile ions. The electrode material in a supercapacitor is selected to be very porous in order to maximize contact area with the electrolyte. This allows supercapacitors to have a higher charge storage density in comparison to a regular capacitor, but this comes at a slight conductivity cost. Therefore, non-porous, highly conductive current collector layers are usually added to the outsides of the electrodes to connect the supercapacitor to any external circuitry. Three possible geometries of a supercapacitor are shown in Figure 2. Layers may be stacked in a parallel-plate structure, placed side by side in a co-planar geometry, or even formed axially.

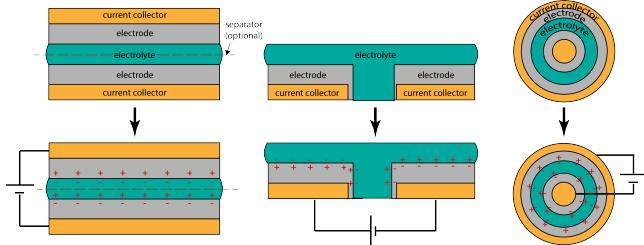


Figure 2: Left: parallel-plate supercapacitor geometry. Middle: co-planar supercapacitor geometry. Right: axial supercapacitor geometry. When a voltage is applied, charge layers build up at the interfaces between the electrodes and electrolyte.

When a voltage is applied between the two electrodes, ions within the electrolyte migrate towards the two electrode interfaces, causing the buildup of opposing electrostatic charge layers at each interface. Unlike the charging and discharging processes of batteries, which utilize semi-irreversible reactions that involve ions moving across layer boundaries and changing the chemistry of those layers, the charging and discharging processes of supercapacitors are completely reversible and do not involve chemical reactions. Thus, supercapacitors can theoretically be charged and discharged a limitless number of times. Even though they are generally capable of storing less energy than batteries and tend not to be suitable for applications requiring continuous operation over long periods of time, commercial supercapacitors have very high power

density for their size due to the porous nature and high specific surface area of the electrodes. In addition, they can both charge quickly and supply large amounts of current quickly, unlike batteries. Commercial supercapacitors are commonly available in coin cell or cylindrical form factors and can be surface-mounted onto printed circuit boards. They are used today in numerous applications, such as power storage and delivery for regenerative braking, back-up power for static random-access memory (SRAM), and electric grid stabilization [81, 127]. As we shall discuss, VIMS can find somewhat unconventional but invaluable uses as short-term power sources (lasting for a few days or less) for many small electronics such as piezoelectric buzzers, LEDs, Inertial Measurement Units (IMUs), and low-power microcontrollers.

Given these principles, we next present material selection considerations for designing VIMS.

3.2 Materials

There exists an overwhelming number of candidates for each layer of a supercapacitor that materials scientists and chemists have developed to optimize particular aspects of a supercapacitor's performance. The materials comprising the highest performance supercapacitors today are often nano-engineered materials and require fairly complex synthesis in an advanced chemistry lab or cleanroom [83]. In this section, we distill the key properties of each layer that are needed to successfully make a functional supercapacitor and apply them to commercially available, cheap, and household-safe (mostly edible) materials to make VIMS.

3.2.1 Current collector. The important features of a good current collector are high conductivity, mechanical flexibility, and, to some extent, low cost. Edible gold leaf is a widely available ingredient that fits these criteria. As cheaper alternatives, we also explored carbon-based options, such as rolled graphite foil, which yields equally good results. Although less costly than gold leaf, we found that edible silver leaf serves as a poor current collector, perhaps due to surface oxidation that results in high contact resistance with electrodes.

3.2.2 Electrode. A supercapacitor's storage capacity is largely a function of the surface area of the interfaces between the electrodes and electrolyte. As such, the electrode material should be conductive but, unlike a current collector, porous. Activated charcoal is an obvious choice for VIMS, as it is one of the most successful materials even in conventional supercapacitors [94] and is also obtainable in a cheap and edible form. Activated charcoal has many household uses and is available as a loose powder, in edible capsules as a dietary supplement, and in pouches as air or water filtration material. It can even be made at home: wood or other organic matter may be burned to make charcoal, which can in turn be "activated" by adding calcium chloride, bleach, or lemon juice.

3.2.3 Binder. A binder is used to turn the electrode and electrolyte base materials into forms that can be printed or spread. The binder should be an agent that can be dissolved in water or another environmentally friendly solvent to create a viscous paste or gel that does not have large clumps. Good candidates are additives used to thicken liquids or doughs in cooking or baking, such as eggs, carboxymethyl cellulose (CMC), and cornstarch.

3.2.4 Electrolyte. An electrolyte is an ionic liquid or gel that allows for the migration and distribution of electrolyte salts and can be spread onto the electrodes without completely dissolving them. Commercial supercapacitors often use lithium salts, but VIMs should use an electrolyte comprising non-toxic salts, such as sodium chloride (NaCl, or table salt), calcium chloride, and/or potassium iodide, dispersed in a gel. The simplest way to make an electrolyte is by dissolving salt in a polar medium, such as water, and adding a binder, such as one described previously, as a thickener. Although water is one of the cheapest and most abundant solvents, one drawback of water-based electrolytes is that the maximum voltage that can be applied between two electrodes should be capped to 1.5V to avoid the hydrolysis of the water in the electrolyte (i.e. the permanent breakdown of water molecules into hydrogen and oxygen gases) [112]. VIMs may be chained in series to overcome this voltage limitation. Still, VIMs made with water-based electrolytes also need to be encapsulated to prevent evaporation, which otherwise causes a VIM to become non-functional in 1 week, depending on environmental conditions. Although possessing lower salt solubility than water, glycerin, a food-grade ingredient that is also a plasticizer, is a good alternative that allows for higher working voltages and also does not dry out over time.

3.2.5 Separator. If the electrolyte used is thin in consistency, a separator between electrodes is needed to prevent inadvertent electrical shorts. This separator should be electrically insulating but thin and permeable to allow the ions in the electrolyte to migrate across it. Paper is a low-cost and widely available candidate, though edible options such as rice paper or seaweed [113] can also be used. If the electrolyte used is thick or viscous enough to prevent the electrodes from touching, a separator is not needed at all.

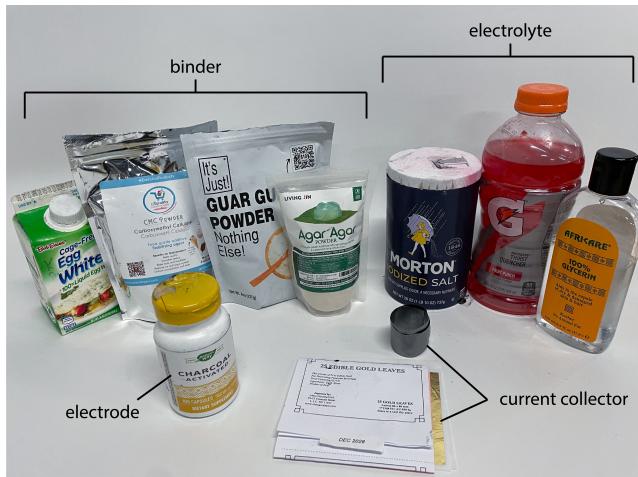


Figure 3: A selection of ingredients that we used for making VIMs.

3.3 Selecting Materials

In practice, when crafting VIMs, designers may pick and choose different materials based on considerations such as their local availability, ease of storage and handling, cost, aesthetics, and even

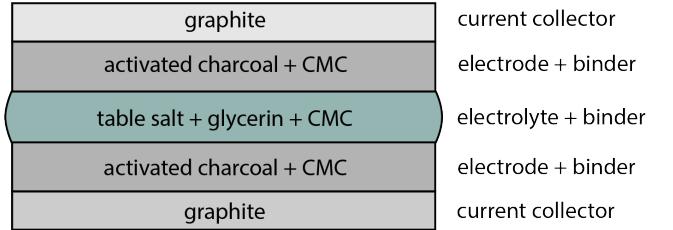


Figure 4: The stack-up for our exemplar VIMs.

culinary factors. For example, edible gold foil may be desirable from an aesthetics standpoint or may be necessary when making edible VIMs. However, it is costly, and its delicate nature makes it difficult to handle. Graphite is an easy-to-handle, less expensive alternative that is equally effective as a current collector. Table 1 offers a list of some material candidates for each layer that we tested, along with details that might help determine their desirability in different locations or for applications. The materials we use for our exemplar VIM recipe, described and characterized in the rest of this paper, are highlighted in bold. Of course, performance is also a noteworthy facet, though we found that several materials, such as CMC and guar gum, can be used interchangeably when layer thickness is normalized. Example detailed comparisons, along with links to purchase all materials, are available in our Supplemental Materials. Figure 3 depicts some of the specific ingredients we used. All materials listed are non-toxic (many of them edible), can be made flexible and thin to allow them to conform to arbitrary surfaces, and can be shaped by hand or hand tools.

In the rest of this paper, we operationalize the principles outlined thus far and detail the fabrication, characterization, and applications of our most successful VIM recipe.

3.4 Exemplar VIM

The stack-up for our exemplar VIM is shown in Figure 4. We utilize rolled foils of 127 μm -thick graphite, a naturally occurring form of carbon that can be used as plant food, as our current collector and substrate. Graphite is cheap, abundant, conductive, and available in flexible sheets that function as both a substrate and a current collector. As in commercial supercapacitors, we use activated charcoal as our electrode. We extract powdered activated charcoal from dietary supplement capsules. We select CMC as our binder, as it forms electrode and electrolyte inks that are spreadable (unlike less viscous choices like sports drinks) and odor-free (unlike other choices like eggs, cheese, or chitosan). CMC is a cellulose gum that is a common thickener and emulsifier used in ice cream, biscuits, and candy. It also yields the highest performance VIMs by a small margin when compared to guar gum and chitosan (see Supplemental Materials). For our electrolyte, we mix table salt with glycerin and CMC. The cost of materials to make a VIM of the size shown in Figure 5 (11cm^2) is approximately \$0.13 (USD), with \$0.12 of that being the cost of graphite.

3.5 Fabrication Process

The fabrication process for making VIMs is straightforward and can be conducted in a standard makerspace. We fabricate VIMs by

Table 1: VIM Material Candidates and Selection Considerations

Layer	Material	Availability	Cost	Form and handling	Aesthetics	Culinary factors	Performance
Current collector	Gold leaf	Online retailers, specialty culinary stores, art stores	4¢/cm ² (\$50/g)	Delicate sheets. Needs careful handling with tweezers, needs to be mounted to a substrate.	Associated with luxury. Shiny, gold-colored.	Tasteless. Used as edible decoration.	Good - comparable to graphite.
	Graphite	Online retailers, potentially homemade	0.5¢/cm ² (19¢/g)	Sheets/rolls. Can be cut w/ hand tools or laser/vinyl cutter.	"Industrial" steel look. Gray.	Not conventionally consumed.	Good (baseline)
Electrode	Activated charcoal	Online retailers, pharmacies, home improvement stores, potentially homemade	2¢/g	Black powder or granules. Can stain clothing.	Black, opaque	Tasteless. Used as additive for color in breads, pasta.	Good (industry standard)
Binder	CMC	Online retailers, specialty culinary stores	4¢/g	Powder. Shelf-stable. Results in spreadable gel.	Milky-colored	Tasteless. Used as thickener.	Good (baseline). Stable over months.
	Guar gum	Online retailers, specialty culinary stores	1¢/g	Powder. Shelf-stable. Results in spreadable gel.	Milky-colored	Tasteless. Used as thickener.	Good. Stable over months. Comparable to CMC.
	Chitosan	Online retailers, potentially homemade	7¢/g	Powder. Needs to be dissolved in vinegar. Shelf-stable. Results in spreadable gel.	Mostly clear with yellow hue	Not vegetarian. Has slight odor.	Stable over months. Slightly lower power density than CMC.
	Agar agar	Online retailers, specialty culinary stores	3¢/g	Powder. Needs to be warmed to spread. Warps as it dries.	Clear with brown hue	Tasteless. Used as thickener and in jellies.	~1 week shelf life due to warping
	Gelatin	Most grocery stores, online retailers	2¢/g	Powder. Needs to be warmed to spread. Warps as it dries.	Clear	Not vegetarian. Tasteless. Used as a thickener and in jellies.	~1 week shelf life due to warping
	Egg whites	Grocery stores, farms	1¢/g	Liquid or powder. Perishable. Coagulates when heated.	Mostly clear	Not vegetarian. Common food.	~1 week shelf life due to warping
Electrolyte (solvent)	Water	Grocery stores, nature	<0.1¢/g	Liquid. Evaporates over time. May squeeze out during assembly.	Clear	Tasteless.	1.5V max per cell. ~1 week shelf life due to evaporation
	Glycerin	Online retailers, grocery stores, pharmacies, specialty culinary stores	0.7¢/g	Thick liquid w/ oily consistency.. Doesn't dry out. Flammable >200C.	Clear	Sweet-tasting. Used as thickener/sweetener.	Good (baseline). Stable over months.
Electrolyte	Cheese	Grocery stores worldwide, potentially homemade	1¢/g and up	Solid blocks. Perishable. Needs to be cut or melted to spread or shape. Warps as it dries.	Opaque, white, yellow, or orange. Waxy.	Common food. Not vegetarian. Has odor.	Lower power density. ~1 week shelf life due to drying/warping
	Table salt	Grocery stores worldwide, harvested	0.7¢/g	Granular. Can take time to dissolve depending on solvent.	Colorless	Common ingredient in many dishes.	Good (baseline)
	Sunscreen	Online retailers, grocery stores, pharmacies	5¢/g	Gel or liquid. Dries over time.	White	Not edible.	~1 week shelf life due to evaporation
	Sports drink	Online retailers, grocery stores, pharmacies	0.5¢/g	Powder or pre-mixed in water. Requires encapsulation to prevent squeeze-out.	Ranges in color, depending on drink	Salty, sweet. Often consumed with flavor additives.	Lower power density if dissolved in water
Separator	Paper	Online retailers, office supply stores	0.3¢/g	Sheets. Can be cut w/ hand tools or laser/vinyl cutter.	Ranges in color and feel	Not conventionally consumed	Only needed if electrolyte is runny
	Seaweed	Online retailers, specialty culinary stores, harvested	10¢/g	Sheets. Can be cut w/ hand tools.	Dark green, "leafy" look	Salty, umami taste. Common in Asian cuisines.	Only needed if electrolyte is runny

hand, but we note below where steps may be automated to facilitate higher throughput. The most time-consuming steps are preparing the electrode and electrolyte inks – up to 5 hours, largely due to the slow dissolution of salt in glycerin. However, these inks may be prepared in large batches and kept in sealed containers with no special storage requirements, allowing ad hoc fabrication to take only 10 minutes.

First, the electrode and electrolyte inks are prepared. For the electrode (<10 minutes total if not pre-prepared), activated charcoal and CMC are mixed in a 20:1 weight ratio (w/w) and dissolved in water (1:6 activated charcoal:water w/w). We wish to use as much activated charcoal as possible to maintain conductivity; just enough water is added to create a spreadable ink, and just enough CMC is added for gelling (to prevent the electrode from simply returning to a loose powder form upon drying). Glycerin is added as a plasticizer to prevent cracking during drying in a 10:1 activated charcoal:glycerin weight ratio. The ink is stirred for 5 minutes.

CMC may be swapped for other binders listed in Table 1 without modification to this step.

Next, the electrolyte is prepared (4.5 hours total if not pre-prepared). Table salt is added to glycerin at a ratio of 80g table salt:1kg glycerin. A good electrolyte has an abundance of mobile ions, so we choose this concentration because it is roughly the solubility of NaCl in glycerin at room temperature. To speed up dissolution, the solution is stirred at 800rpm on a temperature-controlled hotplate at 120°C for 4 hours or until the salt is completely dissolved. Glycerin's flash point is 199°C and can safely be heated to temperatures lower than this.³ Water can also be added to facilitate the dissolution of salt, but as previously noted, the presence of water limits the working voltage of the resulting VIMs [112] so must be evaporated subsequently. CMC is then added as a thickener at a weight ratio of 1:5 CMC:glycerin solution, and the mixture is stirred by hand and left

³<https://www.sigmaldrich.com/US/pt/sds/sigma/g2025>

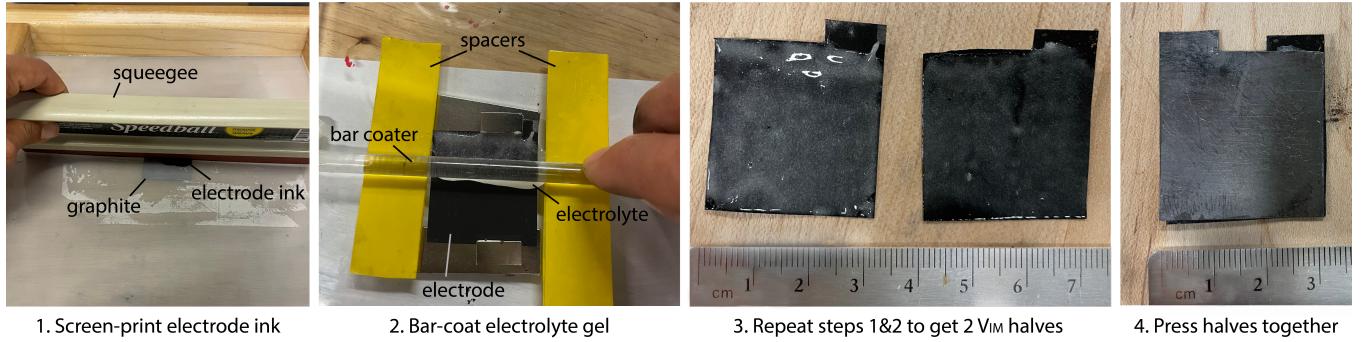


Figure 5: Fabrication of VIMs. 1. Electrode ink is screen-printed onto pre-cut current collectors. 2. After drying, electrolyte gel is spread onto the electrode-coated current collectors via blade-coating. 3. This is repeated on another current collector to get 2 VIM halves. 4. After drying, the 2 halves are pressed together, with the electrolyte sides facing one another.

to gel and homogenize for 30 minutes. The resulting electrolyte is thick enough to hold its shape but still spreadable with a rod or stick. When using water instead of glycerin, more binder is needed to achieve the proper viscosity (1:2 binder:water).

The next step is to form the electrode on the current collector (5 minutes). The electrode mixture is screen-printed onto the graphite current collector, which also serves as a substrate (Figure 5). It is then left to dry on a hotplate at 120°C for 5 minutes. This is repeated to make a second electrode. After screen-printing, the electrodes are 150µm thick. Screen-printing is a common technique for forming thin ink layers. It can be performed by hand, as we do here, with a screen and squeegee, but it also can be done on industrial machines for mass production. Alternatively, the electrode ink may be deposited by a 2D plotter with a syringe attachment (similar to the method described in [2]). If ultra-thin gold foils are being used instead of graphite, they must first be mounted to a substrate for mechanical stability. There are no electrical requirements for substrate materials; one may use separator materials as listed in Table 1 or any other material that has desirable mechanical properties for the target application. Gold foil may be mounted to a substrate by simply wetting the substrate with water or egg and using tweezers to gently drop the foil onto the surface.

The electrolyte layer is then formed on the electrodes (5 minutes). The electrolyte ink is applied to the dried electrodes via blade-coating, an alternative to screen-printing that is more suitable for thick or gelatinous media (Figure 5). Blade-coating is a simple technique that is commonly performed by a machine for the industrial-scale manufacturing of organic electronics, but it can also be done by hand, as we do here, with a glass rod and spacers that define the layer height. Two spacers are made from layers of electrical tape that are stacked until they are each 400µm thick. An electrode is placed between the spacers. A generous amount of electrolyte is then applied to one side of the electrode between the spacers, and a glass rod is pressed on the spacers and then drawn across the area of the electrode to evenly spread the electrolyte. The samples are again dried on a hotplate at 120°C for 5 minutes. If using a water-based electrolyte instead of a glycerin-based one, the drying step is skipped to prevent complete evaporation of the electrolyte.

Finally, the two VIM halves are pressed together, with the newly dried electrolyte sides facing one another. Once dried, the electrolyte we use is flexible but firm. It holds its shape when pressed and does not squeeze out, so a separator is not necessary. If using a less viscous electrolyte without any binder, such as a sports drink, a separator should be placed in between the two halves to prevent electrical shorting. The separator also acts to absorb some liquid electrolyte and prevent it from completely squeezing out during assembly.

3.6 Customizing Geometry

Depending on the application, it may be more aesthetically favorable to make co-planar VIMs that expose the color of the electrodes (see Figure 2). For co-planar VIMs, fabrication is complete after the application of the electrolytes – no sandwiching is needed. The fabrication procedure that we have described is not readily extendable to the axial configuration of Figure 2, but because all layers are thin and conformable, parallel-plate VIMs may be rolled into a cylinder if such a geometry is desired. Additionally, VIMs may be bent, cut, or torn into arbitrary shapes. Examples of a few basic geometric and aesthetic variations are shown in Figure 1. Such modifications may even be made after VIMs are initially fabricated and tested, so they may be easily adapted with minimal material waste as a prototyper iterates upon their design.

4 CHARACTERIZATION

4.1 Electrical Characteristics

Supercapacitors can be electrically characterized by a multitude of metrics, such as energy density, capacitance, equivalent series resistance (ESR), and temperature dependence. Here, we offer a subset of measurements that we believe are most applicable from the perspective of a designer who needs to decide if VIMs can provide sufficient energy to power a given direct current (DC) application. Namely, we present (1) charging characteristics: voltage and current vs. time under constant-voltage and constant-current charging schemes; and (2) discharging characteristics: voltage on a VIM vs. time (a) under no load (i.e. self-discharge) and (b) under

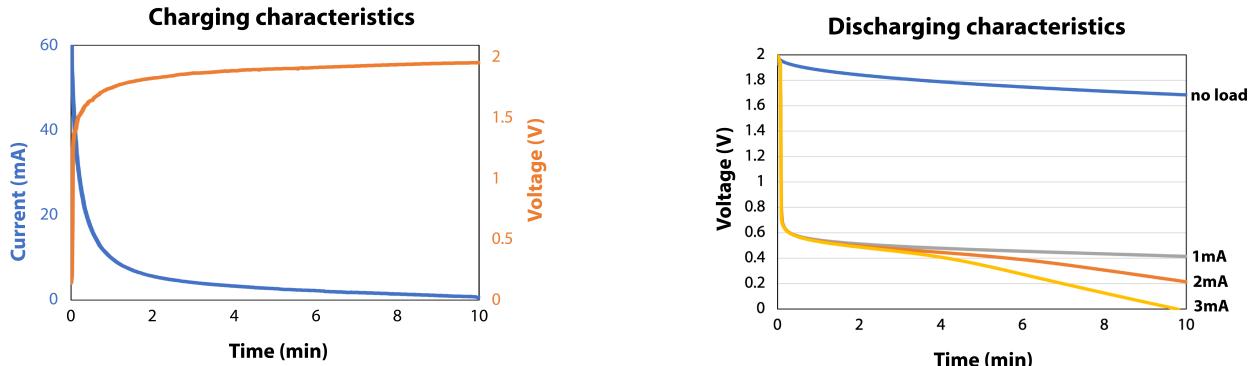


Figure 6: VIM current (left y-axis) and voltage (right y-axis) under constant-voltage charging to 2V. Design is 11cm² in area.

different current loads. More measurements, such as Galvanic discharge curves and capacitance measurements, are available in our Supplementary Materials.

4.1.1 Charging Characteristics. One benefit of supercapacitors in comparison to batteries is that they may be safely and very quickly charged to full capacity – on the order of seconds, in the case of commercial supercapacitors. Because fires and other permanent damage from over-heating are not concerns, VIMs may be charged with practically no limit on charging current. Figure 6 shows the charging current vs. time of a VIM 11cm² in area charged to 2V under a constant-voltage charging scheme. The VIM reaches >1.9V within 5 minutes. We consider it “fully” charged when the charging current drops below 1mA, which occurs after 9 minutes.

VIMs may be more quickly charged by using a constant-current charging scheme with higher current. Under a charging current of 100mA, a VIM reaches 2V in 5 seconds. Thanks to their flexibility to charge under varying current, VIMs can also be directly connected to solar panels or other energy harvesters without the need for a charge regulator.

4.1.2 Discharging Characteristics. Unlike batteries, the voltage that a supercapacitor holds drops over time, both with and without a connected load. This makes the customary metric of amp-hours for estimating battery life a poor one for estimating VIM life. Figure 7 shows discharge characteristics of a single VIM (11cm² in area) under different loads. Prior to each trial, the VIM is charged to 2V for 10 minutes. For these tests, we use a standard DC power supply plugged into a wall outlet for charging. When no load is applied, the VIM slowly discharges due to a leakage current of 40µA through the VIM itself (measured as the steady-state current when the VIM is fully charged), with the voltage discharge rate decreasing as the absolute voltage drops. After 2 hours, the VIM has 1V remaining, and 24 hours later, the VIM has 0.5V.

The bottom plot in Figure 7 also shows the voltage discharge rate of the VIM under different loads, measured after 8 minutes of loading; this metric can be used to roughly estimate the total operational time of a VIM for a given application – assuming a constant current load, the expected operational time is simply the

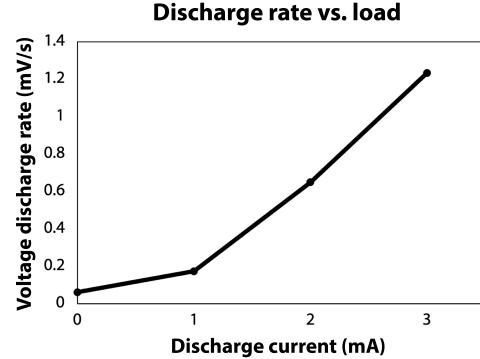


Figure 7: Top: voltage vs. time under different constant current load conditions. Bottom: Discharge rate (linear estimate at the 8 min mark) vs. current loading. Design is 11cm² in area.

tolerable voltage drop of the application divided by the VIM’s voltage discharge rate. However, in reality, the actual time a VIM can last under a given load is more complicated. First, although voltage is expected to drop linearly under a constant current load, due to stray resistances and capacitances, it is not in fact linear. Most notably, as can be seen in the top plot of Figure 7, there is a large initial drop in voltage when a DC current load is applied. This is due to the DC internal resistance (DCIR) of the VIM, which is a combination of the resistances within each layer and the contact resistances between layers. For commercial supercapacitors, this is generally less than 10Ω. For VIMs, this value is much higher and is estimated to be 500Ω (calculated from the 2mA discharge curve on the left plot in Figure 7 as the initial voltage drop divided by the load current). This results in an instantaneous 1.5V drop. While VIMs’ high DCIR is a limitation, it can somewhat be overcome by chaining VIMs in series, thus summing together their voltages (see Figure 8). With just 4-5 small VIMs, we can reasonably unlock many possible applications that require common input voltages such as 3.3 or 5 V.

In contrast to charging and discharging conventional batteries, charging and discharging VIMs do not chemically change the composition of VIMs, so they may be theoretically rapidly charged and discharged virtually endlessly without degradation in performance.

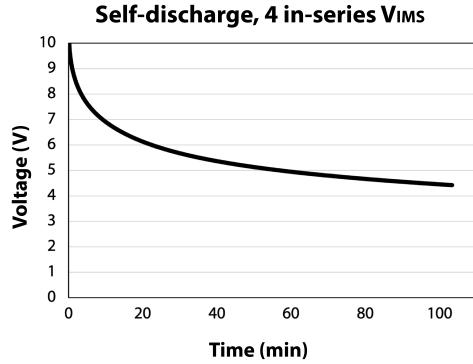


Figure 8: Self-discharge characteristics of a chain of 4 VIMS connected in series and charged to 10V for 3 minutes.

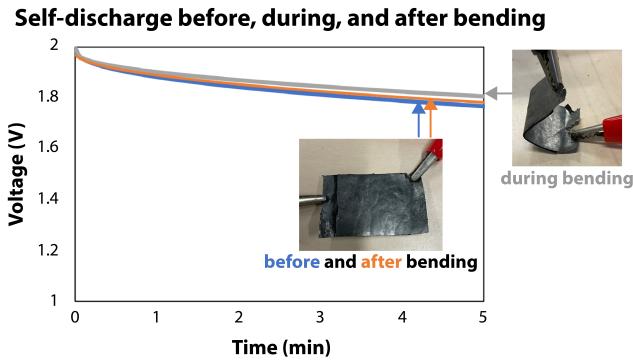


Figure 9: Voltage discharge curves for a VIM before bending to 90 degrees (red), during bending (gray), and after bending (blue). Leakage decreases during bending, and characteristics are recovered once the VIM is re-flattened.

Example charge/discharge cycling charts at different charging currents are available in our Supplemental Materials. We did not perform a detailed stress test, but we have charged and discharged individual VIMS over at least 100 cycles across 3 months with no noticeable change in performance.

4.2 Mechanical Robustness

As previously mentioned, VIMS may be arbitrarily bent or rolled. As seen in Figure 9, when a VIM is bent to 90 degrees, its self-discharge curve actually improves slightly, exhibiting a very small 7% decrease in the discharge voltage vs. time slope. This may be attributed to the slightly increased surface area-to-thickness ratio, and thus total capacitance ($C \propto A/t$), during bending. When unbent, the VIM's original characteristics are restored.

VIMS may also be cut or reshaped after they are fabricated to make one or more VIMS of different shapes. The resulting pieces are functional, with their energy storage capacity scaling with the new area of each piece. Our exemplar VIM recipe additionally does not dry out or warp over time. Thus, VIMS are stable for months when stored under ambient indoor conditions; subsequent testing of VIMS

3 months after initial fabrication and testing yielded indistinguishable electrical characteristics. They remain mechanically flexible. Alternate VIMS made with, for example, water-based electrolytes or cheese do dry, warp, and crack as liquid evaporates, rendering them non-functional within 1 week. To prolong working lifetime, those VIMS may be sealed with a thin encapsulation material, such as melted beeswax or chitosan, which can be brushed onto a VIM. For applications that undergo bending, a flexible encapsulation material (i.e. chitosan instead of beeswax) should be selected.

4.3 Backyard Degradation

Even though VIMS are reusable and rechargeable, they are also designed to be disposable and decomposable in a very short period of time without specialized industrial conditions. In fact, our exemplar VIMS may be beneficial additions for garden soil health. Activated charcoal and graphite are immediately usable as soil conditioner [53]. Glycerin is also known to be a degradable soil additive that can promote soil nutrient retention and healthy microbial growth [11]. CMC has been reported to decompose under normal environmental conditions within 14 days [34]. The example materials that we listed in Table 1 are similarly ones that are well known to be decomposable.

As a sanity check, we buried a VIM in our yard to observe decomposition for ourselves. We buried the VIM under 5 cm of soil in a sunny garden during the summer. The soil was alluvial soil (loose clay and silt) with a moisture content of 30% as measured by a handheld moisture meter at the beginning of the study. The VIM was dug up and photographed every 15 days and was also weighed starting from day 45 (see Figure 10). Over the course of 60 days, the VIM had visibly degraded, with almost everything between the graphite current collectors no longer present; the graphite pieces were mostly intact but had become very brittle, breaking into pieces when lifted from the soil. Only 30% of the VIM's mass remained after 60 days. Plants near the burial site appeared to remain healthy. This is unsurprising, since we intentionally selected components that are known to be decomposable.

Of course, decomposition times depend on environmental conditions, and they also vary based on VIM material selection. We buried a VIM with edible gold leaf electrodes in the same garden plot as the VIM with graphite electrodes. The gold leaf VIM lost 80% of its mass within 1 week. We hypothesize that this is in part due to the fact that the gold leaf is a mere $0.1\mu\text{m}$ in thickness compared to the $127\mu\text{m}$ thickness of the graphite foil.

5 APPLICATIONS

We now present several use cases for VIMS. The first leverages the customizability of VIMS to enable new aesthetic and form factor flexibility when it comes to electronics prototyping and showcases energy storage as a first-class design element. The second and third leverage the decomposability of VIMS to unlock novel interactive technologies that are in turn decomposable in their entirety.

5.1 Electronics Prototyping

Because VIMS can take on arbitrary shape and, to some extent, color and texture, they may be double as decorative design elements and power sources. For example, edible gold foil may simultaneously

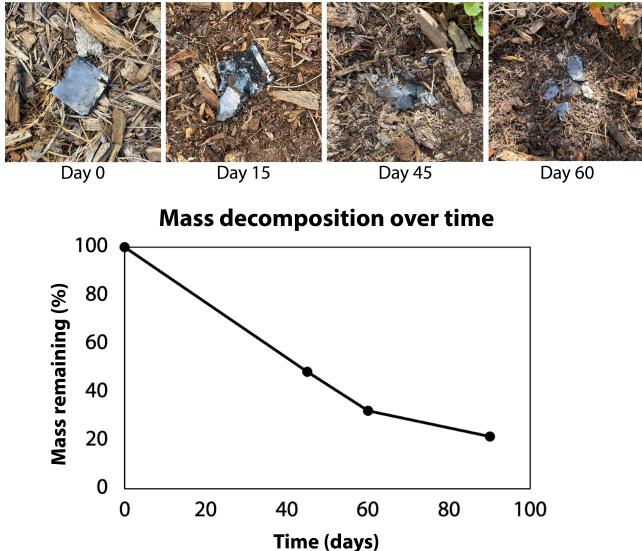


Figure 10: Top: series of images qualitatively showing VIM degradation across 60 days buried in backyard soil. Bottom: plot of mass remaining over time.

serve as a VIM current collector and as a material for creating a gilded appearance. VIMS built on this gold foil can be extremely thin and conformable, wrapping around otherwise awkward corners or curves of a design. Additionally, VIMS eliminate the need for battery-related enclosures, such as spring clips or protective casings. Figure 11 shows the before and after photos of a small digital clock with its coin cell battery replaced by 5 co-planar VIMS in series, integrated into a decorative pattern on the body of the clock. The clock remains operational on a single 5 minute charge for over 2 hours. We also successfully powered a temperature sensor with a chain of 3 VIMS (see Supplemental Material). Other modules with specs well within VIMS' operating regime include piezo buzzers⁴, LEDs⁵, vibration motors⁶, and IMUs⁷. Series of 5 or fewer VIMS can be expected to power such applications for minutes, hours, and potentially even days, depending on frequency of activation.

5.2 100% Degradable On-Skin Display

A noteworthy benefit of VIMS, as we have described, is that they are fully decomposable. In addition to increasing the eco-friendliness of prototyping with conventional electronics, a particularly exciting possibility that this property opens is in the development of fully degradable, and even edible, interactive systems that were not possible before. As two examples, we describe an on-skin electrochromic display that can be powered all day and a new shocking eating experience enabled by VIMS.

⁴e.g. Multicomp ABI-014-RC, <https://www.newark.com/pro-signal/abi-014-rc/indicator-piezo-transducer-function/dp/83R9240>

⁵e.g. onsemi CAT3661 <https://www.onsemi.com/products/power-management/led-drivers/dc-dc-led-drivers/cat3661>

⁶e.g. Vybrronics motors <https://www.digikey.com/en/product-highlight/j/jinlong/z4tl2b03715452-low-current-vibration-motor-series>

⁷e.g. Maxim MAX21100 IMU <https://datasheets.maximintegrated.com/en/ds/MAX21100.pdf>

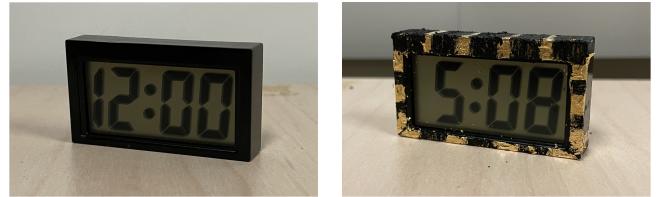


Figure 11: Left: a commercial digital clock powered on a coin cell battery. Right: clock with coin cell battery removed and powered by decorative VIMS (5 co-planar units in series)

Fashion is a domain that is fitting for fully decomposable interactive interfaces. Despite laudable ongoing efforts to shift away from the culture of “fast fashion,” social pressures to continuously refresh wardrobes persist. Some accessories are only appropriate to don in certain occasional situations; it is still often considered a faux pas to re-wear outfits or accessories [91]; fads inevitably fall out of style. Thus, when it comes to smart wearables for accessorizing and personalizing a look, there is value in offering technology that is targeted for only a few hours’ worth of wear and can then be disposed of in an environmentally responsible way.

Coupled with other sustainable materials, VIMS allow us to design electronic wearables that do not result in any landfill. Inspired by DuoSkin [49] and other on-skin interfaces [64, 114, 116], Figure 14 shows a 100% decomposable on-skin display that we developed [96]. It is powered by 4 co-planar VIMS connected in series. The VIMS are mounted on a cotton bracelet (see Figure 12) with pine resin, a natural sticky substance that can be used as an adhesive. The cotton used is a leftover strip from a sewing project and is dyed with chlorophyllin, a natural green pigment. Field studies have shown that cotton fabrics can fully degrade in soil under ambient temperatures (25–29°C) within 1–3 months [73, 115]. Other alternatives that are decomposable include paper, untreated or naturally dyed hemp, lyocell, and linen (flax). The graphite current collectors at each end are wrapped around the back of the bracelet for contact to the electrodes of the display. Alternatively, if preferred, VIMS may be adhered directly to the skin, either with a skin-safe, biodegradable adhesive or by mounting VIMS onto surgical tape that can then be placed on the skin, as seen in our Video Figure. VIMS are thin and flexible enough to conform to and move with the skin, and when the latter strategy is used, the feeling is akin to wearing a fabric bandage. For a more luxurious aesthetic, gold current collectors may be used instead of graphite ones.

Operationally, the system is a 2-state display whose transformation is triggered by the application of a lotion, cream, or other electrolytic gel [96]. The display comprises a single layer of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), a common conductive polymer that, while not inherently biodegradable on its own, is non-cytotoxic [74] and becomes biodegradable in the presence of hydrogen peroxide, which is widely available and environmentally friendly [22]. The PEDOT:PSS is mixed in a 7:3 ratio with dimethyl sulfoxide (DMSO), a natural solvent extracted from wood that is available as an anti-inflammatory prescription or dietary supplement. The PEDOT:PSS/DMSO ink is both highly conductive and electrochromic. It serves as both the electrode and

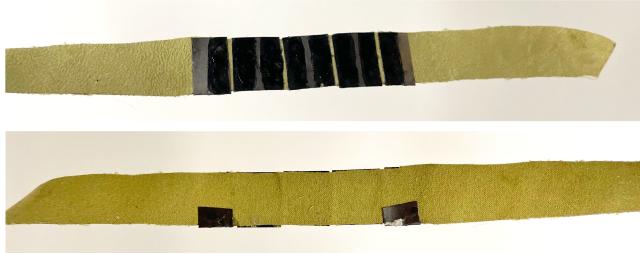


Figure 12: The front (top image) and back (bottom image) of a VIM “bracelet” for powering a 100% decomposable wearable.

active electrochromic layer, eliminating the need for separate toxic indium tin oxide or other electrode layers that are often used in conventional electrochromic displays. The schematic of the system is shown in Figure 13. Initially, the system is in an open circuit configuration, with no power consumption. When lotion or another activating conductive gel or cream is applied, it acts as an electrolyte, closing the circuit and allowing free ions to migrate towards the electrodes. A reduction reaction at the negative electrode and an oxidation reaction at the positive electrode occur. PEDOT:PSS becomes noticeably darker under reduction, leading to color changes in the design that saturate in a couple of seconds. Very little lotion – just enough to cover the electrodes and the gap(s) between them (<1μm thick layer) – is needed to induce this transformation. Additionally, the power consumption associated with this change is very low, with 60μA of current being consumed when 5V is applied. Voltages as low as 0.5V may also be used to cause this reaction, though this comes at the expense of switching time (which increases to 30 seconds). The on-skin display is quasi-bistable and can hold its color-changed state for over 10 minutes or until the lotion is wiped off or absorbed by the skin, at which point it slowly reverts to its original state. A chain of 4 VIMs holds more than enough charge to power this wearable over the course of a whole day with multiple lotion applications.

To fabricate the on-skin display, we simply airbrush a thin (<1μm) layer of PEDOT:PSS ink onto paper surgical tape. The desired design is patterned with a laser cutter, and we use transfer tape to transfer the design onto the forearm (Figure 14). A charged VIM bracelet is then tied onto the wrist such that the on-skin display’s electrodes contact those of the VIM bracelet.

An example envisioned interaction is shown in Figure 14. An individual may apply a customized patch as they would a temporary tattoo and connect it to a VIM bracelet. When lotion or activating gel is applied onto the skin, it completes the electrochromic “circuit,” and selective areas of the design turn deep blue. This could be used to simply make a fashion statement, to reveal a hidden message from a friend who gifted the wearer the design, or to serve as an aesthetic, positive feedback mechanism or reminder for lotion-related self care, among other applications, which are discussed in more detail in [96]. At the end of the day or week, when the wearer is tired of the design, the whole system may simply be peeled off from the skin like a band-aid. It can be soaked in hydrogen peroxide for a day to effectively degrade the PEDOT:PSS ink [22] and then

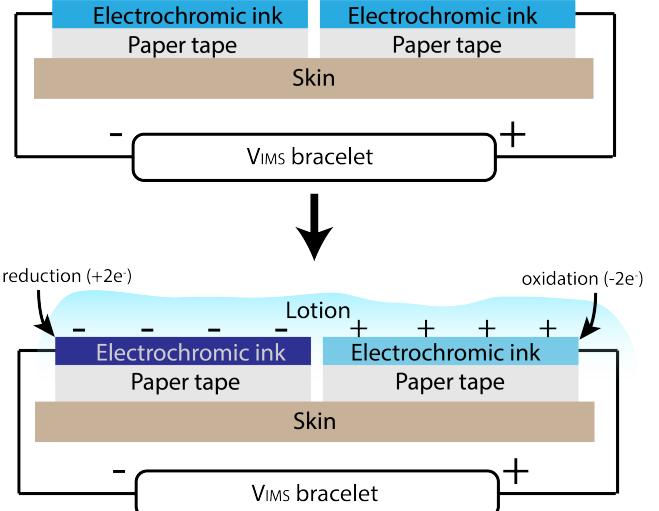


Figure 13: Schematic of our electrochromic on-skin display. Applied lotion acts as an electrolyte and causes a color-changing redox reaction at the electrode interfaces.

tossed into the backyard, where it quickly decomposes and enriches the soil.

5.3 New Edible Experiences

Human-food interaction has recently garnered great interest within the HCI community and has been the subject of a Special Interest Group at CHI 2022 [27] as well as several workshops at CHI, CHI PLAY, and DIS [32]. By definition, eating is an experience that is ephemeral and thus potentially another domain for which VIMs are ideal. Our exemplar VIM design may be made fully edible by replacing the graphite current collectors with edible gold foil, enabling new, sustainable interactions during the experience of eating. This VIM variation on its own is relatively neutral in taste, which makes it a good candidate for emulating different tastes with current. The tongue can perceive microamps of current, with reported thresholds as low as 5μA [100]. Ranasinghe et al. created a “Digital Flavor Synthesizer” that, in conjunction with heating and cooling elements, used 20–180μA of current to simulate sour, spicy, and minty tastes [88, 89]. An edible VIM is capable of delivering these levels of current. Figure 15 plots the current of an edible VIM charged to 2V versus time when shorted through a 47kΩ resistor, which approximates the resistance of a human tongue. A future user study is needed to more accurately characterize how such VIMs would taste, but based on characterizations from existing research, the delivered amounts of current may be perceived as mild salty or sour [88]. Edible VIMs may be disguised as decorative gold flakes on a cake to deliver a tantalizing surprise to the eater. Alternatively, by using cheese as an electrolyte, the VIM may instead improve the taste of cheap cheese, emulating the taste of a much more expensive, aged cheese with subtle flavor notes. We might imagine yet other applications, such as augmenting or restoring eating experiences for people with taste dysfunction and powering digestible electronics for internal health monitoring. Edible VIMs

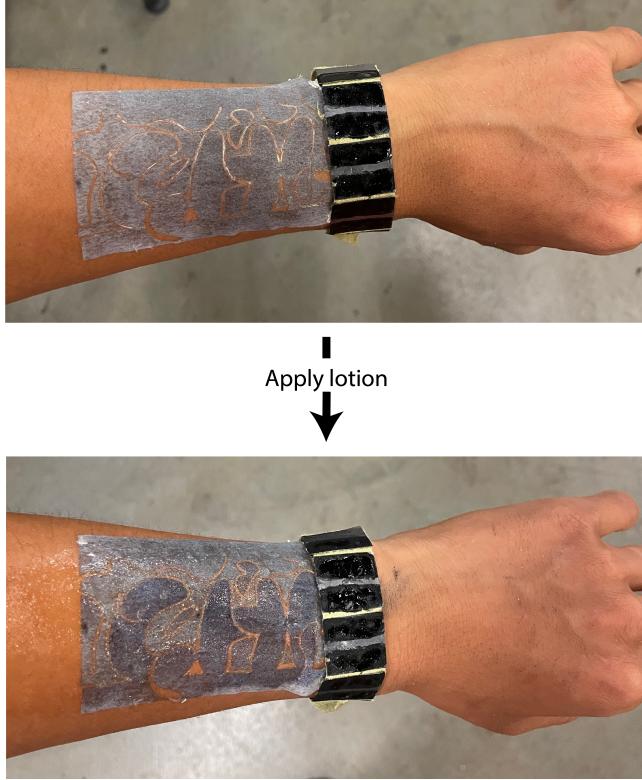


Figure 14: A 100% decomposable wearable. VIMs are chained in series as a bracelet and contact the electrodes of a simple PEDOT:PSS-based electrochromic design. When lotion is applied as an electrolyte, parts of the design change color, revealing a hidden message.

could also allow programmable flavors to supplement Augmented or Virtual Reality (AR/VR) experiences, triggering flavor profiling consistent with what a user sees and thinks they are eating.

6 DISCUSSION AND FUTURE WORK

6.1 Democratizing Energy Storage Design

A key advantage of VIMs with respect to existing work is their ability to be safely fabricated at home with commercially available, non-toxic materials. While we believe that this is the first demonstration of decomposable supercapacitors made with DIY-friendly techniques, modern DIY communities of non-expert makers and technologists have been thriving for over a century [56]. The HCI literature has seen numerous demonstrations of DIY assistive technologies [44, 70], biology [35], e-textiles [16, 18], cell phones [71], and home electronics [93]. Although they are more laborious than simply ordering pre-packaged, commercial goods, DIY approaches to fabrication, relying on cheap and widely available technologies such as screen- and inkjet-printing [52, 55], have been touted as democratizing technological engagement, empowering makers, fostering emotional attachment, and increasing engagement with nature, among other benefits [36, 44, 67, 104]. DIY material development in

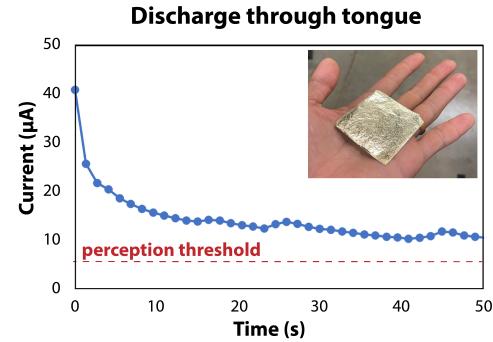


Figure 15: Current vs. time for a charged edible VIM shorted through a 47kOhm resistor, which approximates a human tongue. Inset: image of VIM tested.

particular has also been shown to provide valuable opportunities for personal expression and experiential learning [10, 78, 92].

In more formal classroom and workshop settings, DIY making has been cited as an approach to help children develop an inclination to study Science, Technology, Engineering, and Math (STEM) [24, 65] and to engage new communities in technological design and prototyping [86, 95]. Requiring nothing more than what can be found in a classroom or makerspace, the design of VIMs could be a valuable addition to an educational curriculum. Making VIMs requires more effort than, say, ordering batteries online or pressing “START” on a digital fabrication machine, but VIMs could be packaged as self-contained kits with pre-portioned quantities of materials to facilitate fabrication, allowing our design to be more widely adopted and understood. Other kinds of kits might contain large batches of pre-mixed electrode inks and electrolytes, allowing VIMs to be fabricated in just a few minutes with minimal equipment. Such kits could be used in classrooms, hackathons, special events, or even just in personal settings, supporting budding electronicists’ creative freedom, encouraging the blending of technology with art and craft [19], and also helping makers better understand the environmental costs of powering their systems.

The accessibility of VIMs fabrication rests on the assumption that ingredients are locally available. While there may exist particular locations where this is not in fact the case (and where the aforementioned kits cannot be shipped to), the design of VIMs is fortunately readily adaptable to different materials that might be more available or economical in different locales. For example, in locations where CMC is difficult or costly to obtain, eggs (e.g. on a farm with birds) or agar agar (e.g. by the sea) are suitable replacements with only minor performance differences. The materials we experimented with, listed in Table 1, make up just a small subset of options. In this way, we believe that VIMs can be made by a wide range of populations and, when coupled with energy harvesting methods, can offer small-scale power solutions in remote environments and developing communities.

We see the large-scale efforts enabled by DIY culture as critical to inspiring new uses of sustainable materials and encouraging novel aesthetics for VIMs. We have confidence that by following

our basic design guidelines, motivated makers can find success with many different materials for VIMS that we have not explored, maybe even discovering and publishing their own variants and related artifacts, as has been the case for hardware kits [18]. Open-source libraries of natural materials, such as *materiom*[87], could further help facilitate the discovery of new material combinations. Future workshops could test these claims and reveal new insights, designs, and breakthroughs that our team could never discover alone.

Still, DIY-friendly approaches are not without concerns when it comes to sustainability. It is possible that excessively lowering barriers to fabrication could lead to an overzealous fabrication of goods instead of practicing reuse and repair [67]. Furthermore, while we believe that DIY-friendly approaches can accelerate discovery of novel, better VIMS, we understand the value of enabling the eventual large-scale production of sustainable designs, which could start as DIY approaches, to truly maximize both technical capabilities and public awareness of related environmental issues. It may be fruitful to guide explorations of new materials and aesthetics for VIMS with techniques that are adaptable to higher-throughput technologies, such as inkjet-printing or roll-to-roll manufacturing.

6.2 Choosing the “Right” Sustainable System Design

In the Related Work section, we noted that there are several promising approaches that use non-decomposable materials and electronics to create systems that can sustain themselves virtually forever without batteries. Furthermore, high-capacity batteries based on lead acid or lithium ion, while containing toxic components, can last for long stretches of time, and some would argue that batteries will only become more eco-friendly as industries focus increasingly on recycling technology [46]. So how might one choose *which* “sustainable” power scheme to use for a given portable design? Factors to consider include the duration and frequency of an interaction, voltage and current needs, local availability of materials, and availability and capability of energy sources, such as wireless chargers, RF sources, solar power, or body heat, among others. For many applications, VIMS are in fact not the most desirable option, both in terms of performance and in terms of overall environmental impact. For example, for applications that require operation over long periods of time, relying on VIMS would likely be inconvenient, as they discharge relatively quickly and would thus have to be re-charged frequently. For high-power applications, non-decomposable conventional batteries might instead be a wiser – or sometimes the only – choice. For certain microwatt-scale applications in environments where there are reliable RF networks, ambient backscatter communication, possibly in conjunction with energy harvesting, could be the most fitting solution.

VIMS are ideal options for interactions that only occur once or over a short period of time, or happen where no wireless energy transfer is available. Like ambient RF, VIMS are more than capable of providing the voltage and current needed to power piezo buzzers. Furthermore, VIMS can provide minutes of power for many interactions that require more than 1mW of power, such as resistive heating, LED driving, micro-motor actuation, or positional sensing with an IMU. Such applications demand more instantaneous power

than current energy harvesting technologies are capable of delivering. Hobbyists have even modified Arduino microcontrollers to run on 3.3V and <10µA of current [54], which VIMS could easily sustain for hours and potentially days. Additional opportunities include any designs that might benefit from VIMS’ fast and fuss-free charging. For such applications, our VIMS design approach can offer a more eco-friendly solution than what currently exists. As we have described, fashion and food are two domains that are ripe with opportunities. Other potential scenarios include powering temporary environmental sensors in remote environments or powering transient electronics that may be dangerous if obtained by hostile parties. Applications will only grow in number and scope as work in ultra-low-power systems continues to burgeon [90].

As future work, we hope to integrate VIMS with decomposable energy generation or harvesting solutions to further broaden the realm of decomposable interactive systems. VIMS as presented can already be charged with commercial solar cells, but to enable more systems that can be responsibly disposed of in their entirety, it is a logical next step to explore the viability of more eco-friendly energy harvesting solutions to continuously power a system without the need for periodic recharging. Electrogenic organisms that generate electricity could be one avenue of exploration [23, 62]. Admittedly, this will be a challenging undertaking, as even energy harvesters engineered with non-sustainable materials generally generate less than 1mW of power.

6.3 Limitations

Despite their potential, it is indeed difficult to imagine VIMS replacing conventional batteries or existing power storage in many – perhaps even most – applications in the near future. Even when it comes to temporary wearables, edible technology, and other domains for which we believe VIMS are well suited, there remains much work to be done to better understand and overcome limitations. Systematic user studies are needed to better understand how VIMS might feel on the skin across different populations, what other kinds of substrates they might be applied to, and how robust they are to various activities and environments. Additionally, VIMS are durable enough to be stored unsealed in an indoor environment and can operate in the presence of small amounts of moisture, but being inherently decomposable, they are susceptible to prolonged exposure to elements such as rain, sweat, and saliva, limiting their lifetime. In some cases, solutions may be straightforward. For example, encapsulating VIMS with materials such as beeswax or chitosan can mitigate the effect of moisture (encapsulation can also be a strategy for prolonging the working lifetime of VIMS made with water-based electrolytes, which otherwise evaporate). Still, large amounts of moisture will ultimately degrade a VIM’s performance by potentially dissolving critical layers or otherwise hastening degradation. VIMS in their current state are thus not appropriate for wet or underwater situations. Future experimentation may uncover more water-resistant material sets, but it is likely that such materials would also be less easily decomposable, which may be a competing design consideration.

Moreover, designing within the limitations of “safe” workflows and degradable materials comes with performance tradeoffs. VIMS

are inherently low capacity and low performance relative to commercially available supercapacitors. Increasing storage capacity and decreasing self-discharge likely requires more advanced material engineering. For example, capacitance scales with electrode area, so nanoscale texturing would be advantageous. Another major performance limitation of VIMS, as noted previously in the Characterization section, is a high DCIR, which causes a large initial drop in voltage when a VIM is connected to a load. To decrease the contact resistance between layers, and therefore lessen the voltage drop, layers should be deposited in succession in a vacuum or inert gas environment, and inks should be ultra-homogenized such that constituent particles are extremely small ($<0.1\mu\text{m}$). Finally, chemists today have remarkable abilities to concoct specialized materials with just the right combination of desirable properties, and these materials unsurprisingly lend themselves to much higher-performance supercapacitors than the results of a DIY “scavenging” approach. Still, we do believe that there is great potential for VIMS to improve in performance beyond what we have presented by encouraging broader communities to simply try more material combinations and different fabrication techniques. Furthermore, even with their current capabilities, many applications – ones that are low power, operate on the order of 1 day, and can be powered by VIMS with their current capabilities. As discussed in the previous sub-section, VIMS can be used for the rapid prototyping of low-power electronics and wearables, for sustainable electronics education, and for edible electronics. For these designs and many others beyond what we alone can imagined, switching to VIMS can generate new degrees of both design flexibility and environmental friendliness.

7 CONCLUSION

Designers of battery-powered electronics like our friend Alice from the Introduction often resort to adjusting their designs at the last minute to accommodate batteries that are too large, too rigid, or too long lasting relative to the intended designs. This paper presents VIMS – fully decomposable supercapacitors that are capable of powering small applications for over one day on mere minutes of charge time. Instead of searching for and waiting for her lithium ion battery to arrive after finishing initial prototyping, Alice could have incorporated a flexible, gold VIMS chain as an aesthetic feature of her ring design, iterating simultaneously upon all elements of the design in concert with one another instead of waiting until the end of the design process to search for an energy storage solution. Furthermore, the decomposability of VIMS might have inspired Alice to choose decomposable alternatives for other elements of her design as well, allowing her entire system to be used as compost for her garden after her event. VIMS are well suited as an alternative to batteries for many interactions and systems that are relatively low power and ephemeral or temporary in nature. They not only provide the missing piece needed for entire interactive systems to be decomposable; they are also easily fabricated at home with a variety of different materials, opening new doors in design customization, sustainable materials development, and green electronics education. This is just the beginning for what we hope is a new relationship between designers and power.

ACKNOWLEDGMENTS

We are grateful for the generous support from the NDSEG Fellowship program. Additionally, we thank the thoughtful reviewers for their constructive feedback on this research.

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