
Photovoltaic Materials for the Design of Self-Powered Interfaces and Interactions using Shadow Detection

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Abstract

In this paper, we review and describe how different photovoltaic (PV) materials can be used for designing self-powered interfaces and interactions using indoor ambient light to both power the device and to detect simple shadow-based gestures. We consider seven points when comparing the material technologies: device efficiency, device stability, device manufacturability, device flexibility, photovoltaic cell optical transparency, material toxicity and finished product aesthetics. We provide a step-by-step PV fabrication process for the HCI community. This will help HCI researchers to consider the opportunities and challenges when designing PV-based self-powered IoT applications with an HCI context.

Author Keywords

Authors' choice; of terms; separated; by semicolons; include commas, within terms only; required.

CCS Concepts

•**Human-centered computing** → **Human computer interaction (HCI)**; *Haptic devices*; User studies; Please use the 2012 Classifiers and see this link to embed them in the text: https://dl.acm.org/ccs/ccs_flat.cfm

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Introduction

For sustainability, IoT devices could be designed to consume low power or be self-powered and require low maintenance without needing battery replacement every few years. Interactive IoT devices could be implemented using low power interaction technologies or use the self-powering technology to enable interaction. In this context, we consider the photovoltaic (PV) technology for both energy harvesting and gesture recognition using the ambient light. Gesture recognition systems using ambient light should not be affected by changes in the intensity, number, and/or position of light sources in the environment. Furthermore, the system should also not assume any control over the lighting infrastructure and should work with all types of ambient light sources [14].

Related Work: Technological Possibilities

Photovoltaic (PV) materials

Many PV technologies are available. In this section, we give a brief overview of the main PV technologies and their relative advantages for indoor gesture sensing applications. We consider seven points when comparing the material technologies: device efficiency, device stability, device manufacturability, device flexibility, photovoltaic cell optical transparency, material toxicity and finished product aesthetics.

Silicon Photovoltaics:

The most ubiquitous solar energy harvesting technology in use today is silicon-based photovoltaics. Silicon comes in a variety of crystalline structures, e.g. crystalline silicon, polycrystalline silicon and amorphous silicon. Amorphous silicon is by far the cheapest and most prevalent in use in consumer photovoltaics.

The theoretical efficiency of silicon photovoltaics is limited by the Shockley–Queisser efficiency limit. Crystalline silicon

solar cells are theoretically capable of achieving more than 30% efficiency [4, 1, 2]. The amorphous silicon solar cells have much lower efficiencies. Amorphous silicon solar cells have been reported to exhibit efficiencies of up to 8.8% [12]. Silicon solar cells are durable and provide relatively high efficiency; however, they remain generally quite rigid. One way of producing flexible panels with silicon PV cells is to incorporate them into flexible substrates by weaving tiny silicon PV cells into a fabric [13]. Silicon PV requires a lot of energy to make (e.g., pure silicon is ‘pulled’ from molten silicon via the Czochralski process), so it is energy intensive and, as such, not particularly environmentally friendly.

Gallium Arsenide (GaAs) Photovoltaics:

Researchers have reported GaAs solar cell efficiencies of up to 29.1% [15]. The one major disadvantage of GaAs photovoltaics is their prohibitive cost.

Dye-sensitized Solar Cells (DSSC):

Alternative, more environmentally friendly photovoltaics exist. Electrochemical photovoltaics in the form of dye sensitised solar cells have been around for many decades. Research continues to improve the efficiency of these devices. Although the maximum theoretical power conversion efficiency under standard test conditions is around 32% [11], to date the state-of-the-art efficiency is only 14.3% [5]. Some of the advantages of DSSCs, include good stability, easy construction, environmentally friendly dyes and other materials in a wide variety of colours. A major disadvantage is perhaps the liquid electrolyte used within the cell which is susceptible to leaking from the cell cavity.

More recently, researchers have investigated other low-cost photovoltaic technologies. Printable photovoltaics are particularly interesting. The two main technologies are organic photovoltaics (OPV) and metal-organic perovskite solar cells (PSCs).

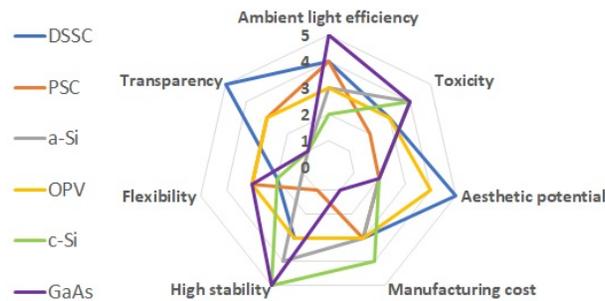


Figure 1: Visual comparison of the six main PV technologies. Here we see that DSSCs offer the best optical transparency and aesthetic potential. Although the manufacturing cost of DSSCs is relatively high, fabrication of DSSCs is simple and can be carried out in any suitably equipped maker lab

Organic Photovoltaics (OPV):

OPV cells with efficiencies of over 16% have been reported [6]. Compared to silicon photovoltaics, organic (polymer) PVs are light-weight and flexible, making them ideal for applications requiring tailored sizes, shapes and colours. One of the main disadvantages of polymer PVs is their relatively low efficiency and high rate of degradation, especially in harsh outdoor conditions.

Perovskite Solar Cells (PSCs):

State-of-the-art PSCs [9] research reported the world record efficiency of 27.3% in 2018 [10]. Major disadvantages of this technology include material toxicity and the extremely poor stability of PSC materials in air atmosphere.

We next describe and discuss the fabrication flow of some of the user manufacturable devices and how they can be incorporated into HCI designs.

Fabrication Process

In this section, we present the fabrication processes of decorative and functional DSSCs, PSCs, and OPVs. For designing IoT applications, these cells can be fabricated in a cleanroom using a relatively simple processes that can be followed by any suitably trained graduate student.

DSSCs: Fluorine doped Tin Oxide (FTO) coated glass substrates are washed with detergent (Helmanex 5% in DI water) and sonicated for 15 minutes, rinsed in DI water, and followed by 2 minutes sonication in each of DI water, Acetone, and Isopropyl alcohol before drying in N_2 stream. Substrates were then plasma cleaned for 10 minutes in an O_2 plasma to remove any organic material and improve wettability. A nano-porous titania layer is deposited on the FTO by screen printing or doctor-blading before sintering in an oven or hotplate at 450 degrees centigrade. The sintered nano-porous titania is then dyed by over-night emersion in ruthenium dye (Ruthenizer 535-bis TBA from Solaronix) solution. Excess dye is rinsed off with ethanol before the substrate is dried in a N_2 stream. The top plate has filling holes drilled before the plate is cleaned, as above, in preparation for quasi-transparent layer of activated platinum deposition Platisol T (Solaronix) by spin coating. The top plate is then dried on a hot plate. In the final stages of DSSC fabrication, a sealing gasket laser cut from 60 μm thick thermoplastic Surlyn® is sandwiched between the two plates and pressed together at ≈ 120 degrees centigrade for 30 seconds. The cavity formed between the top plate and dye-sensitised substrate is filled with iodide/tri-iodide electrolyte by capillary action, before the filling holes are sealed.

PSCs: For the PIN structure cells: Indium doped tin oxide (ITO) coated glass substrates were washed with detergent (Helmanex 5% in DI water) and sonicated for 15

minutes, rinsed in DI water, and followed by a 2 minute sonication in each of DI water, Acetone, and Isopropyl alcohol before drying in N₂ stream. Substrates were then plasma cleaned for 10 minutes in an O₂ plasma to remove any organic material and improve wettability. To prepare the hole transport layer (HTL), a 0.2 M solution of nickel acetate tetrahydrate in 2-methoxyethanol (12 μ/ml ethanolamine) was spin-coated on an ITO glass substrate at 3000 rpm for 30s, and then annealed at 300°C for 30 minutes. To prepare the perovskite precursor solution, 199 mg of Methylammonium Iodide (MAI) was combined with 605 mg of lead iodide (PbI₂), and 1 ml of a 4:1 solution of Dimethylformamide (DMF): Dimethylsulfoxide (DMSO). The solution was heated at 60°C overnight followed by a filtration through a 0.45 μm PTFE filter. The precursor solution was spin-coated onto the HTL at 4000 rpm for 30 s and crystallised via the antisolvent method wherein 200 μl of ethyl acetate is deposited directly onto the centre of the spinning sample 7 s after the start of the spin. The samples are then annealed at 100°C for 10 minutes. To prepare the electron transport layer (ETL) a solution of 20 mg/ml of the fullerene derivative [6,6]-Phenyl-C61-butyric acid methyl ester (PC₆₀BM) in chlorobenzene is heated overnight at 60°C and filtered through a 0.45 μm PTFE filter. The ETL solution is spin-coated onto the perovskite layer for 30 s at 4000 rpm and dried at room temperature. In order to improve the work-function compatibility between the ETL and the silver contacts a solution of 1 mg/ml of bathocuproine (BCP) is spin-coated onto the PCBM at 4000 rpm for 30 s. Finally, an Ag electrode was deposited by thermal deposition on the ETL.

OPVs: Commercially available indium tin oxide (ITO) coated glass is sonicated in warm (60 degrees centigrade) acetone for 5 minutes. The ITO coated glass substrates are then transferred to a 2% Helmax solution and sonicated for

a further 5 minutes at room temperature, before rinsing in de-ionised water (5 times). Further sonication is carried out as follows: 15 minutes in de-ionised water; 10 minutes in acetone; and, finally, 10 minutes in isopropanol. Drying is carried out overnight on a hotplate at 60 degrees centigrade.

The substrates are treated in an oxygen plasma (ITO side up) for 2.5 minutes immediately prior to zinc oxide layer deposition. Substrates are first sprayed with N₂ to remove any dirt before spin coating @ 4 krpm, 10 krpm/sec for 40 s with filtered (0.45 mm PTFE filter) zinc oxide solution (9.975 wt% zinc acetate dihydrate; 87.249 wt% 2-methoxyethanol; and 2.777 wt% ethanolamine) and annealed on a hotplate at 150 degrees centigrade for 10 minutes. The zinc oxide coated substrates are then transferred to a glovebox (0.6 ppm H₂O ; 439.7 ppm O₂) for deposition of an electron donor polymer layer. The electron donor polymer solution (PCE-10:PC71BM) is spin coated @ 800 rpm, 2 krpm/sec for 90 s, before transfer to a second glovebox (< 0.1 ppm H₂O ; < 0.1 ppm O₂) where the polymer layer is allowed to dry overnight at room temperature.

The final step is to deposit ≈10 nm of MoO₃ and 130 nm of Ag layer by evaporation (without breaking the vacuum between layers) through a shadow mask. See figure.

Since photocurrent is proportional to active area of a photovoltaic cell, it is vital that we aim to utilise the entire cell area for photocurrent generation. Future devices will incorporate transparent/semi-transparent electrodes to achieve this. Future work on OPV cells will include optimisation of OPV layers to maximise VOC and ISC, as well as improving OPV stability, etc. These are all currently areas of intensive active research.

Display technologies

For the purpose of interactive surfaces, visual displays can be split into two categories: (i) Displays that emit light and; (ii) displays that modulate incident ambient light.

Consideration of which display technology to use is based on user requirements. For example, some user scenarios require frequent update of information and graphics, whereas other scenarios may require much less frequent changes in display content, perhaps coupled with a higher level of design aesthetics. Displays may need to blend into the surrounding surfaces and only provide subtle changes to convey messages to the user. Alternatively, the display may only be required to attract immediate attention to convey important safety instructions to users. The way that images and text are displayed determines which display technology is most appropriate. This also sets limitations on how frequently we can update the display and what kind of information we can display.

Liquid Crystal (LC) Displays:

Liquid crystal displays (LCD) are ubiquitous and have been used for decades in all manner of electronic consumer goods. They modulate ambient light or back lighting by either scattering the incident light or rotating its plane of polarisation. The most recent low power LCDs are called polymer network LCDs. These devices scatter incident ambient light. They offer excellent contrast ratio and extremely low power consumption. Although colour LCDs are available, black and white LCDs offer the lowest power consumption. Their electrical and optical performance is comparable to other competing state-of-the-art technologies.

Electrophoretic (e-ink) Displays:

E-ink displays are similar to light scattering LCDs, in that they scatter incident ambient light. Electrophoretic displays are well suited to applications where infrequent changes

are required to the displayed text and images. One common application of e-ink displays is in electronic books. The infrequent change in image display, coupled with long delays before refresh mean that the power consumption of these devices is extremely low.

Electrochromic Displays:

Electrochromic display have previously attracted the attention of the HCI community. They are only able to display two images by means of flipping the electrode polarity. Segmented electrochromic displays allow very limited information to be displayed. Each image transition requires a relatively high peak current. Multi-colour displays are possible, but with greatly increased device complexity [16]. The main advantages of this type of display for the HCI community include long image stability (minutes to hours) and easy fabrication in a suitably equipped maker lab.

Organic Light Emitting Diodes (OLED) Displays:

Organic Light Emitting Diodes (OLED) are a class of light emitting display. These colour displays come in various sizes and pixel resolutions [7]. Being light emitting displays, their power consumption is comparatively high for self-powered IoT applications.

Electroluminescent (EL) Displays:

The final class of display that we will discuss is the electroluminescent display. Like the OLED display, EL displays emit their own light. They are relatively simple to fabricate using printing techniques. Their main disadvantages are the high operating voltages [8] and the limited choice of colours available. Like the electrochromic display, the available user images and text are determined during fabrication.

In Table 1 [3], we compare the electrical and optical characteristics of the three most viable and commercially available displays for integration into self-powered IoT devices. The

| Display Technology | Power consumption | Contrast Ratio | Response Time |
|-------------------------|--|----------------|-----------------------------|
| PNLC | 10 mW @ 1 Hz | 10:1 | 100 ms |
| Electrophoretic (e-ink) | 30 mW @ 1/15 Hz | 7:1 | 260 ms |
| Electrochromic | 1.28 mW/cm ² @100 switches/day | 30:1 38:1 | 200 ms/ 4mm ² |

Table 1: Electrical and optical characteristics of the three most suitable display technologies for self-powered IoT applications

figures show that both PNLC and electrochromic displays offer best (and complementary) characteristics for integration into self-powered interactive interfaces, i.e. PNLC dis-

plays ideal for use where changing information displayed, while EC is useful when infrequent visual prompts are required.

Conclusion

We reviewed the latest PV and low-power display technologies and discussed their efficiency, stability, manufacturability, flexibility, PV optical transparency, material toxicity and finished product aesthetics. Current progress in low-power wireless communications such as Bluetooth Low Energy and ZigBee PRO Green Power, together with low power controller circuit boards will allow to make self-powered IoT devices.

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