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Future Paper based Printed Circuit Boards for Green Electronics: Fabrication and Life Cycle Assessment

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Paper-based electronics have been considered as one of the most exciting technologies in the near future due to sustainability, low cost and mechanical flexibility etc. Even though there have been numerous studies regarding this technology, there isn't any available quantitative study on how paper electronics would minimize the impact to the environment. This work aims to give the first detailed analysis regarding this important question. To this end, we for the first time designed and prototyped the paper-based multilayer printed circuit boards (P-PCB), which show comparable functions to the currently available organic printed circuit boards (O-PCB); yet the P-PCB adopt a "green" preparation process. A life cycle assessment study was performed to quantify the P-PCB's environmental impacts, e.g. Acidification Potential Global Warming Potential, Human Toxic Potential, and Ozone Layer Depletion Potential etc. Our current research reveals that the P-PCB have about two magnitude lower impact to the environment than O-PCB based on the results of the life cycle assessment, which suggests that the P-PCB technique is beneficial for the environment at the regional or global production level. The current study gives useful information and sheds light on the future technological directions for the various paper based electronics studies.

Introduction

Paper-based electronics have attracted considerable interest because of their unique characteristics including flexibility, foldability, lightweight, degradability and low cost. A wide range of devices have been investigated in a paper-based scenario,[1] including transistors,[2, 3] solar cells,[4, 5] supercapacitors,[6, 7] batteries,[8-11] radio frequency identification (RFID) tags,[12-14] antennas,[15, 16] micro-fluidic paper-based analytical devices (μPAD),[17] micro electro-mechanical systems (MEMS),[18, 19] touch pads,[20, 21] flexible displays,[22] OLEDs[23] and microfluidic analytical devices etc.[24] Although these new types of products are considered to be advantageous over the conventional ones in terms of both economic and environmental concerns, there still lacks a systematic evaluation about how and how much the paper-based electronic products could be better than the current counterparts. Therefore it's of considerable interest to carry out a systematic survey of paper-based electronics, i.e. paper-based printed circuit board (P-PCB) technology in this report.

Printed circuit boards (PCBs) are an indispensable part in the electronic industry, which provide support for the integrated circuits and electrical connections for the electronic components. The global PCB market was about 54 billion in 2012, of which China market accounted for almost 40% and is predicted to continously increase in the next five years.[25] However, the conventional PCB is an environmentally harzadous product due to the significantly negative impact along its life cycle. For example, the PCB manufacturing is

Broader Context

The concept of paper based electronics has been brought out for decades and there are many developments about the materials, techniques and applications in recent years. Many reports present the excellent properties of paper based electronics in various applications and discuss the possibilities towards large scale manufacturing, commercialization and product integration. As such, a comprehensive assessment of the paper based electronics is necessary, such as the cost, environmental impact and market size etc. Among them, the environmental impact is one of the most concerned issues, yet there is few research on it and no report available on how much environmental burdens paper electronics have. In this work we developed a multilayer paper based printed circuit board (P-PCB) technque which provides adequate functionalities for common uses; we further conducted the life cycle assessment (LCA) to analysize the environmental impacts of the prototypes based on this technique. With the comparison of the quantitative life cycle impact assessment (LCIA) results of P-PCB and the ordinary organic printed circuits board (O-PCB), we show the great advantages of P-PCB in green electronics, which will cater to the trend of eco-products and sustainability of future electronics.

well known as an energy-intensive and chemical-intensive industry, which involves many chemical processes and materials that are potentially harmful to the environment.[26, 27] It's once reported that the electronic industry caused severe pollution of some rivers around the pearl river delta that contain excessive levels of heavy metals such as copper and lead.[28] What is more, the PCB industry brings about potential environmental issues in the waste disposal and recycling stages. It is estimated that globally, 20-50 million tons of waste electrical and electronic equipments (WEEE) are discarded annually, and a large sum of them are informally collected and recycled especially in those developing countries in Africa and Asia.[29, 30] This problem is more servere in the case of mid-range and low-end electrical devices such as domestic appliances. It is forecasted that the amount of domestic e-waste in China will rise to 5.4 million tons in 2015.[31] The waste PCBs are from all kinds of WEEE, which contain a large amount of toxic substances, such as organic compounds, heavy metals and brominated flame retardants (BFR); these substances can cause serious environmental and health problems if improperly disposed. For instance, Guiyu in Guangdong province, China (Figure S11) may be the largest electronic waste (e-waste) site on the earth.[32, 33] Due to the many primitive recycling operations, 80% of the children in Guiyu were suffering from lead poisoning and the soil there had been found to be so saturated with heavy metals such as lead, chromium and tin that the groundwater becomes undrinkable.[34]

In order to solve these problems, besides imposing more strict regulations by the governments, techncial advances such as replacing the current hazardous materials with more environmentally-benign ones can be a very effective manner. As such, paper-based PCB (P-PCB) technique has been regarded as one of the most promising alternatives to the current organic PCB (O-PCB) technique in near future for green electronics and sustainable development due to the features of sustainability, flexibility, degradability and low cost.

In order to enable a new integration scheme of P-PCB into the current electronic packaging technology so as to achieve the necessary working functions for the future green electronics, a novel prototype of P-PCB needs to be established. The design of this prototype shall follow some basic principles so that the future P-PCB can possess the general functions much resembling to the available common O-PCB. For example, 1) a P-PCB shall possess excellent electrical conductivity in the printed circuit areas to avoid severe resistance loss; 2) the resolution of lines and pitches shall meet the basic requirements for modern electronic packages; 3) it could have a multilayer structure with functional vias; and 4) it shall have adequate reliability which ensures the general applications. Moreover, considering the intrinsic characteristics of paper, a pure additive process seems to be the best choice for the fabrication of P-PCB, such as 3-D printing,[35] inkjet printing[12, 36-38] and screen printing,[39, 40] instead of the current subtractive or a hybrid one which involves with the wet process for both the rigid PCB and flexible PCB. Besides, the wiring material is one of the most important issues for P-PCB, which requires excellent electrical property, reliability and processability etc.

To all these ends, we for the first time established a processing technique for the preparation of the P-PCB and systematically evaluated the environmental impacts. Even though there have been significant advances in the paper based printed conductive circuit technology,[12, 15, 16, 41-45] we selected electrically conductive adhesives (ECAs) as the conductive material for P-PCB in this study; this is mainly because ECAs have been well applied in electronic packaging industry for decades and the recent technical advances of ECAs guarantee the necessary functionalities even when it is printed on paper, such as excellent conductivity, mechanical robustness, outstanding reliability as compared to the conductive inks, and there are a broad spectrum of choices of the high performance polymer resin binder to meet various application scenarios.[46-53] The present work adopts the thermoset polyurethane (PU)-based ECA with micro silver flakes as conductive fillers, which exhibits excellent electrical conductivity and many other superior performance characteristics.[43, 53, 54] Correspondingly, we adopt the screen printing method in this work which is widely used in the printed circuit industry.

Based on our current technique, a series of prototypes of P-PCB with the necessary functionalities were prepared. In order to evalute the environmental costs of P-PCB scientifically, we adopted the life cycle assessment (LCA) method. The LCA is an effective approach to analyze both the energy consumption and environmental impacts associated with a product over its full life cycle all through the raw materials acquisition, production phase, use phase and waste management;[55, 56] and it has been widely applied in the development stage of a new product or technology. The LCA results can provide us a guidance of materials selection, product design, recovery mode and even policy making so that we can focus research efforts on minimizing the burdens of a product while maximizing its benefits. A life cycle thinking is helpful for the eco-design or sustainable design of a new product or technology. So we conducted the LCA method to quantify the environmental impacts and indentify the key drivers of the environmental impacts in the whole life cycle of the P-PCB prototypes.

Methodology

Fabrication and characterizations of the P-PCB prototypes

We designed a pure additive process for fabricating a multilayer P-PCB, which mainly utilizes the techniques of screen printing, drilling and filling. In a typical process, we firstly screen print the polyurethane (PU)-based ECA with the designed patterns on each layer of paper substrate and cure them at 150 ^{o}C, and then adhere them layer by layer using the pressure sensitive adhesive with a position-alignment setup, so that the circuits on different layers are aligned with each other. After that, we connect each layer by punching vertical interconnect access (via) and filling the ECA;

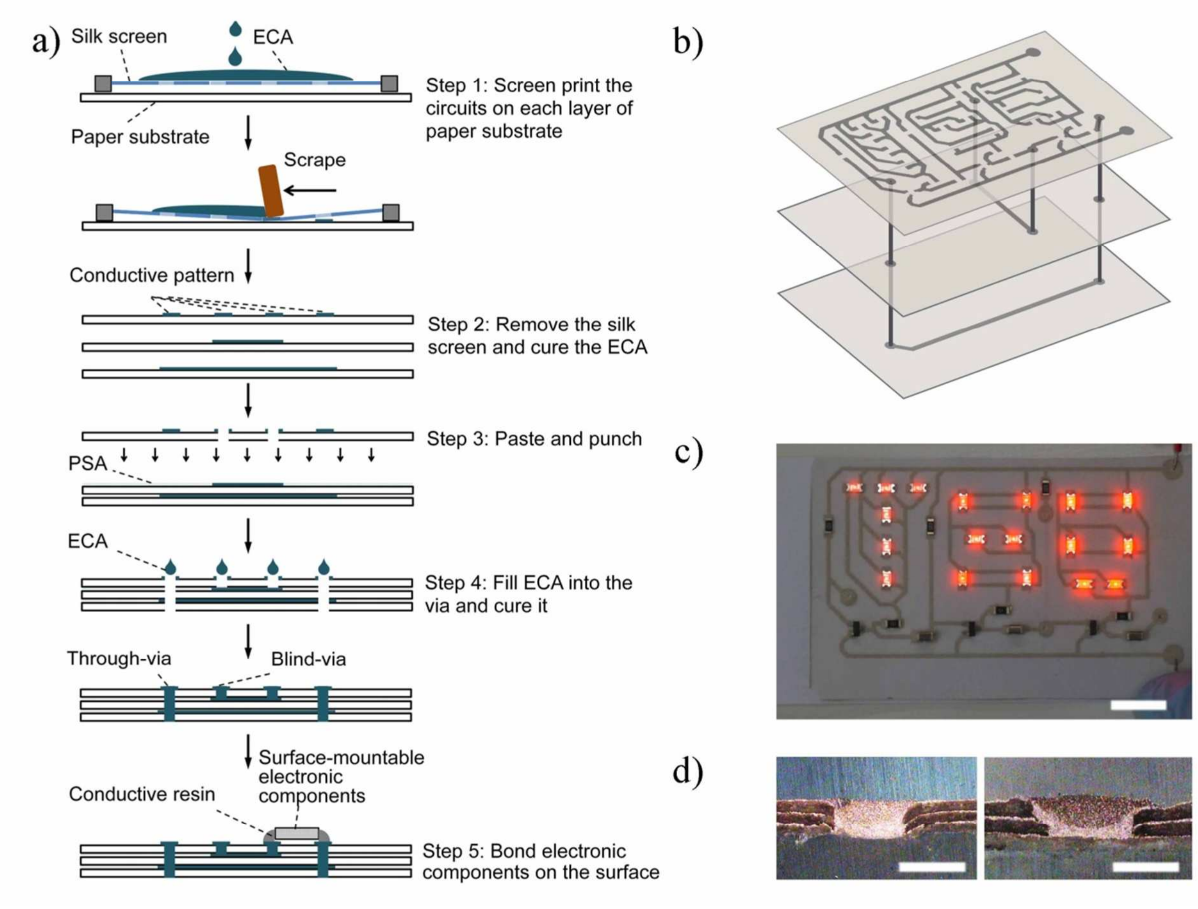

Figure 1. a) A brief flow chart of the pure additive fabrication process of a three-layered P-PCB. b) A schematic diagram of the through-via and blind-via connecting the circuits on different layers of a three-layered P-PCB: the first layer and second layer are connected by two blind-vias, and the first layer and the third layer are connected by two through-vias. c) A prototype of a twinkling LED array showing the letters "THU".(The scale bar is 10 mm) d) Optical microscopic cross-sectional images of a through-via (left) and a blind-via, the ECA filled in the via connected well with each layer. (The scale bar is 0.5 mm)

finally the surface mount devices (SMDs) are mounted onto the surface of the P-PCB with polyacrylate based ECA which can be cured at room temperature. Some times, we need blind vias or burried vias and thus we may adjust the sequence of the adhering and punching steps and the electrical connection would be assured. Using the above methods, the as-obtained P-PCB show analagous functions as compared with the conventional flexible or rigid O-PCB. Figure 1a and b shows the flow chart and a scheme of a typical process for a three-layered P-PCB.

Usually, a two to four-layered circuit board can meet the general mid-range needs for PCB uses, thus we designed several three-layered circuit prototypes (twinkling LED array, doorbell) for P-PCB and replaced the control panel of a tempeture controller with our P-PCB, which worked very well and showed adequate functionality characteristics comparable to O-PCBs (ESI for details†). Here, epoxy based substrate (FR-4) is used for comparison. Then we compared a series of performance characteristics that were essential for PCB applications, including line spacing, moisture resistance, flame retardation, biodegradability, reliability, and dielectrical property of the substrate materials, etc. These tests were performed according to the standards prevalently used in the PCB industry, i.e. the ICP 6013 series.

The materials that we chose were mainly commercial-available printing paper with adhesive stiker (pressure sensitive adhesive) on the back (Avery Dennison Co. America, FASSON series, AW5416), PU resin (Bayer material science AG, Germany, DESMOPHEN 1150 and BL 3175 SN), polyacrylate resin (Koninklijke DSM N.V., Holland, NeoCryl B-725), micro-silver powders (Sichuang Banknote Co., China, Product No. SF01A) and scotch tape (3M). We tailored a position-alignment setup to fabricate this three-layered P-PCB.

Life cycle assessment

The present LCA was conducted according to ISO 14040 guidelines which included four steps: 1) goal and scope definition, 2) inventory analysis which quantifies the materials inputs, the energy inputs, and the environmental discharges through the specified life cycle phases, 3) impact assessment which accumulates flows into different impact categories, 4) interpretation of the results.[57]

In order to demonstrate the environmental advantage of the P-PCB, we conducted a comparative LCA for both P-PCB and the epoxy based O-PCB in terms of materials and processes. As the four-layered epoxy based PCB is commonly used, we defined the functional unit as "fabricating 10000 m^2 of four-layered PCB with paper/epoxy substrate", and we consider the two kinds of PCB to have similar functionalities (we consider them to have the same circuit area, which is 20000 m^2 in this study). The system boundaries are shown in Figure 2. We took the raw materials acquisition, fabrication of PCB and waste disposal into consideration, and excluded the tranportation and use phase in the system boundaries.

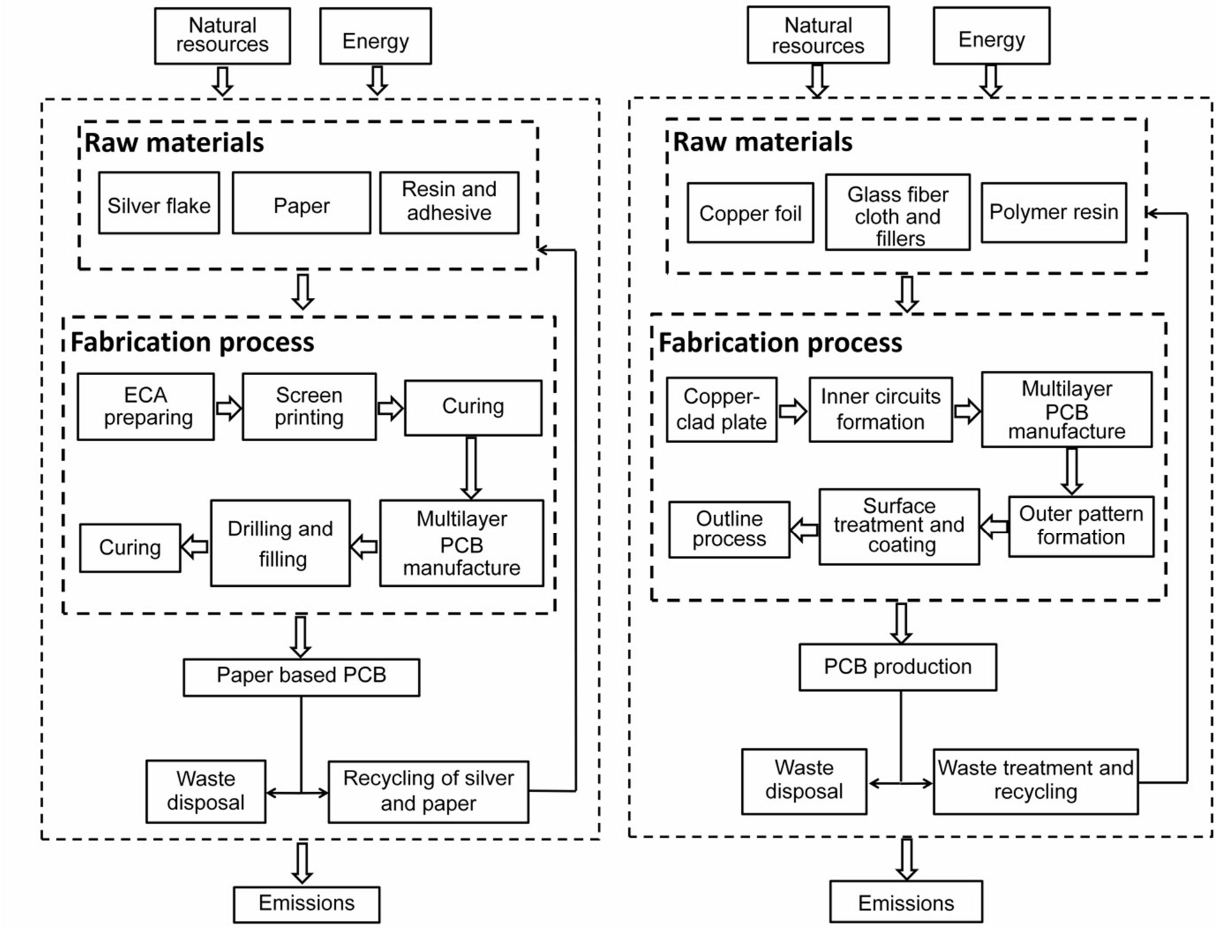

Figure 2 System boundaries of paper based multilayer PCB (left) and epoxy based multilayer PCB (right).

After defining the scope of the study, we established the material inventory by collecting data from local firms in Shenzhen City (Shennan circuits Co., Ltd. and Shenzhen Hangsheng Electronics Co., Ltd.) and the published literatures. Additionally, for P-PCB, we designed and carried out a procedure for multilayer P-PCB fabrications and developed the material inventory based on reasonable assumptions, experimental data and computer models. The main materials inventory data and the collection methods are presented in Table S1 and S3,† all the materials were tracked back to the point of resource extraction, using cradle-to-gate data from the database (Ecoinvent).

The life cycle impact assessment (LCIA) was conducted with the characterization model CML 2001-Apr. 2013 incorporated in GaBi 6.0. In this assessment we considered several most concerned environmental impact catagories: Abiotic Depletion (ADP) (fossil), Acidification Potential (AP), Eutrophication Potential (EP), Freshwater Aquatic Ecotoxicity Potentail (FAETP), Global Warming Potential (GWP), Human Toxic Potential (HTP), Ozone Layer Depletion Potential (ODP), Photochem. Ozone Creation Potential (POCP), and Terrestric Ecotoxicity Potential (TETP). These categories can give full description of the environmental impacts of the P-PCB.

Results and discussions

The comprehensive properties of the P-PCB

We have successfully demonstrated the feasibility of forming 3~10 layered P-PCBs with the procedure we proposed: Figure 1c is a prototype with three layers and Figure 1d shows the cross-section of a through-via and a blind-via of this prototype. The connections of five and ten layers of P-PCB are shown in Figure S3. We can see that the filled ECA connects well with each layer of the printed ECA pattern, and this may guarantee the electrical connection of each layer, which is one of the most important issues of a multilayer P-PCB.

The comprehensive properties of P-PCB are shown in Table 1, and are compared with those of the typical O-PCB. In addition to the advantages of low cost and degradability, the P-PCBs also show excellent reliability performance characteristic during a temperature-humidity (85°C/85RH) aging test (Figure S6) and a thermal cycling (-40~125°C) test. To be specific, the bulk resistivity of the test samples maintained at 1.6×10^{-5} $\Omega\cdot$cm after being aged at 85°C/85RH for 1500 hours, while it just increased to 5.9×10^{-5} $\Omega\cdot$cm after 600 cycles of the thermal cycling test (-40°C~125^{o}C, one cycle in 30 min). Althrough the line spacing, line width and dielectrical property (dielectric loss) are inferior to that of O-PCB, they are still sufficient to meet the requirements for many low density and low-frequency PCB applications. As for the poor performance of flame retardation, moisture resistance and

Table 1 Comprehensive comparison of paper based PCB (P-PCB) and organic based PCB (O-PCB).

	Paper based PCB	**Organic based PCB***
Substrate	Commercially available paper	Epoxy resin/glassfiber/inorganic fillers
Biodegradability	Degradable	Nondegradable
Flame retardation	Poor to fair	Good
Moisture resistance	Poor to fair	Good
Line spacing	~100 μm[1]	~50 μm
Line width	50-100 μm for screen printing[1]	~50 μm
Tensile strength	~6 MPa for printing paper**	---
Flexural strength	---	> 400 MPa
Resistivity of conductive materials	~10^{-5} Ω·cm for 50% Ag loading of PU based ECA**	~2 x 10^{-6} Ω·cm for copper foil
Reliability	> 85°C/85RH 1500h** > -40~125°C/500 cycles**	> 85°C/85RH 1500h > -40~125°C/ 500 cycles
SMT temperature	Room temperature	~240 °C
Dielectric constant	~3 (1G Hz)***	~4.5 (1G Hz)
Dielectric loss factor	~0.132 (1G Hz)***	~0.023(1G Hz)
Cost**	15~30 USD/m^2	90~120 USD/m^2

* We took the FR-4 based PCB for comparison, the performance characteristic parameters are from the product manual of Shennan circuits Co., Ltd.
** The parameters were obtained by experiments, the details can be found in the electronic supplementary informatoin.
*** Tested after drying at 80ºC for 2h and conditioned in a closet with stable temperature and humidity (20ºC, 60%RH).
**** Cost of the P-PCB is calculated based on the prototypes that we prepared (details are shown in **Table S11**) and the cost of the O-PCB (FR-4) is from Shennan circuits Co., Ltd., both contain four layers.

mechanical strength, we can adopt paper-making technique to improve them for future applications (such as adopting proper sizing agent or controlling the surface chemistry[58]). On these grounds, the P-PCB shows comparable functionalities with the conventional O-PCB. To be noted, even though silver is much expensive than copper (about 80 times), it's still quite economical since a pure additive process only involves limited amount of materials and processing steps (Table S2 and S4).

Inventory results of the P-PCB

The main components of the P-PCB are shown in Table 2, and the inventory data are mainly calculated from the model and the prototypes that we constructed before (ESI for details†). The energy consumed in the manufacturing process is estimated with the parameters of the available equipments and the actual consumption in the experiments. From the preliminary assessment results, we may find that although the conductive filler (silver flakes) only makes up 2.83wt% of the P-PCB, its environmental impacts account for a considerable proportion of that of the whole P-PCB. For instance, silver is responsible for more than 75% of the HTP. So we collected the inventory data of the production of silver flakes (Table 3) for a more detailed LCA, and in this way we can focus more on the main causes of the environmental impacts. The detailed inputs inventory is shown in Table S2, which are tracked back to resource consumption.

Inventory comparisons

Figure 3 presents the life cycle inventory results on the mass of emissions for fabricating 10000 m^2 P-PCB and O-PCB. The O-PCB life cycle shows significantly greater emissions to both air and water, which means that the life cycle of O-PCB is more environmentally harmful: the more materials and resource consumptions contribute to more gaseous emisssions like CO_2, SO_2, NO_x and CH_4 etc., more chemical processes involved in the life cycle is responsible for more emissions of Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD) and phosphate.

Environmental impact results of the P-PCB

Figure 4 shows the environmental profile of the P-PCB. The listed are the main raw materials in the production of silver flakes and fabrication of P-PCB. The scores of the environmental impact of each material are normalized in terms of percentage, so that we can define which material is the most contributing factor in the life cycle. For example, the raw material of paper is the main contributor to ADP (51.1%), AP (38.9%), EP (45.1%), FAETP (30.2%), GWP (47.9%), ODP (67.3%), HTP (11.7%), POCP (52.88%) and TETP (40.68%). Because paper is the main component of the P-PCB (~88 wt%), the pulp production and paper production processes are main contributors to the environmental impacts. The Suspended Solid(SS),

Table 2 Material and energy inventory of P-PCB

Component	**Material**	**Weight content**
Substrate	Paper	87.77%
Adhesive	Methyl acrylate	6.58%
Conductive filler	Silver flakes	2.83%
ECA binder	Polyurethane	2.83%
Energy consumption /m^2		0.173kWh

Table 3 Material and energy inventory for silver flakes

Ag flakes/1 kg		
Raw materials	**Amount**	**Unit**
$AgNO_3$	1.573	kg
Ethanol	1	kg
Water	10	kg
NaOH	0.370	kg
Formaldehyde	0.139	kg

Electricity	8	kWh

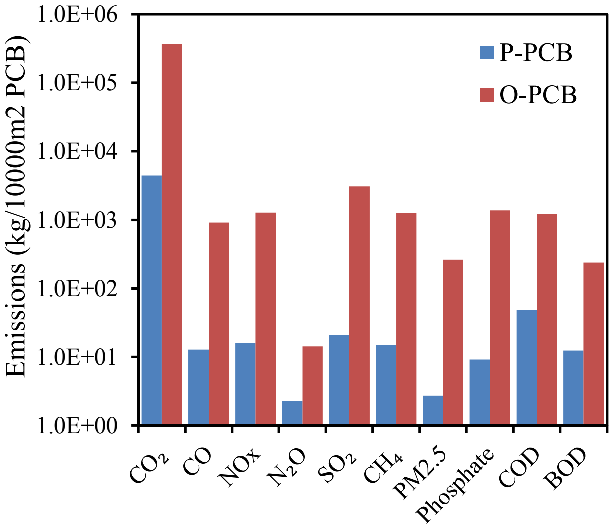

Figure 3 Comparative LCI for P-PCB and O-PCB. PM2.5 refers to particle matter≤2.5 μm; COD refers to Chemical Oxygen Demand; BOD refers to Biological Oxygen Demand.

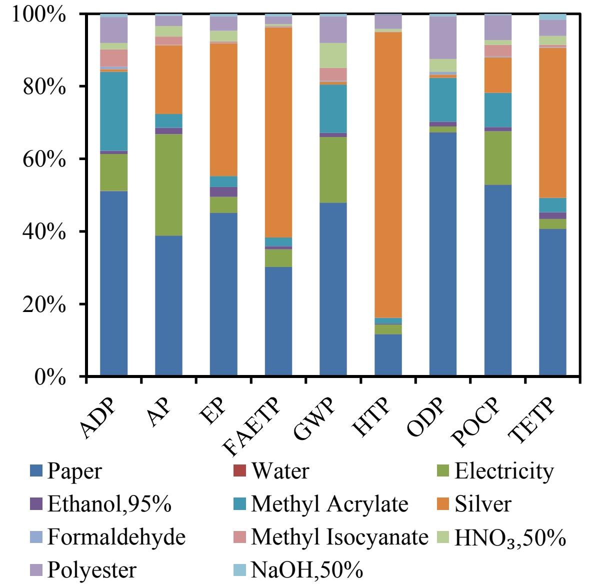

Figure 4 Environmental profile of P-PCB; the main raw materials and consumptions in the manufacturing of P-PCB are listed.

Table 4 LCIA for 10000m^2 P-PCB and O-PCB.

Impact catagories	Impact units	P-PCB	O-PCB	O-PCB :P-PCB
ADP	J	8.51E+10	5.50E+12	65:1
AP	g SO_2-Equiv.	3.63E+04	4.53E+06	125:1
EP	g Phosphate-Equiv.	1.88E+04	2.95E+06	157:1
FAETP	g DCB-Equiv.	3.11E+06	5.81E+08	187:1
GWP	g CO_2-Equiv.	5.55E+06	3.92E+08	71:1
HTP	g DCB-Equiv.	1.03E+07	2.31E+09	224:1
ODP	g R11-Equiv.	3.56E-01	1.85E+01	52:1
POCP	g Ethene-Equiv.	3.31E+03	3.29E+05	99:1
TETP	g DCB-Equiv.	6.49E+04	9.04E+06	139:1

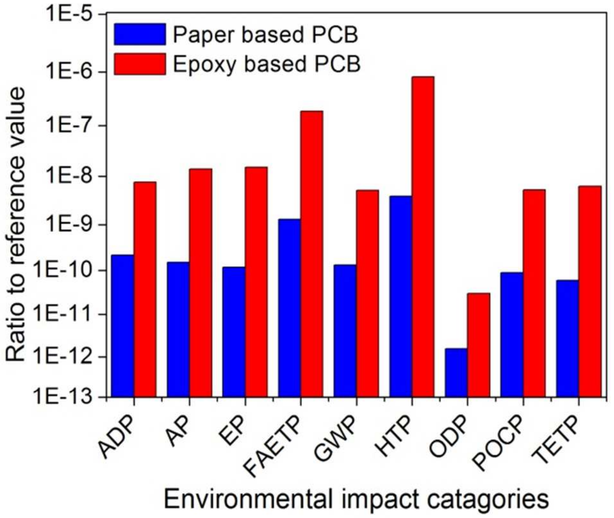

Figure 5 Comparison of the standardized LCIA results of P-PCB and epoxy based PCB

Chemical Oxygen Demand (COD) and Absorbable Organic Halide (AOX) in the pulp production contribute to the EP, FAETP, HTP and TETP; while burdens on ADP are due to energy consumption which is mostly based on fossil fuels. Meanwhile, the alkyl halide emissioin is the primary cause of ODP and the emissions of SO_2, CO_2, NO_x in the pulp production and paper production are the main contributors to AP, GWP, and POCP. [59]

In addition to paper, silver is another significant contributor, despite that it only accounts for less than 3 wt% of the P-PCB (Table 2). This is because the production of silver is a high consumption process: burdens on AP (18%) are due to SO_2 emission from fossil fuel combustion; burdens on EP (36.6%) originate from phosphide and nitride emissions; and the cyanide, biphenyl, mercury, lead, tin discharged in the refining process is responsible for 78.8% of HTP, 57.9% of FAETP and 41.3% of TETP.

On the other hand, the polymer resins, which act as the binder (polyester) and adhesive sticker (polyacrylate), also account for some aspects of air pollution, e.g. AP, GWP, POCP, and ODP because of their potential to discharge SO_2, CO_2, NO_x and halohydrocarbon in the production and disposal phases. Besides, the electricity used in the O-PCB fabrication contributes to ADP, AP, GWP, POCP for its consumption of fossil fuel and emissions of SO_2, CO_2, CH_4, NO_x.

Environmental impact comparisons

Table 4 shows the life cycle impact assessment (LCIA) results of both P-PCB and O-PCB. The flows in the life cycle of O-PCB are much more than those of P-PCB. For example, the emission equivalent weight of HTP, FAETP, EP, TETP and AP in the life cycle of O-PCB is more than one hundred times of that of the P-PCB. This is mainly due to the consumption of copper in the O-PCB production as the life cycle of copper contributes the most to AP (45.15%), EP (63.56%), FAETP (89.52%), HTP (84.02%), TETP (85.09%), POCP (38.06%) as a result of the energy consumption and emissions (gas emissions such as CO_2, SO_2, NO_2 and waste water emission) in the mining and refining processes of copper.[60] In addition, the emission equivalent weight of the other environmental impact catagories of O-PCB is also dozens of times of that of P-PCB.

That is because of the electricity consumption mainly in the electroplating process and the large sum of raw materials such as epoxy substrate, glass fiber and Al_2O_3 etc., which put on much burden on the environment in their life cycle. The contributions of each input of O-PCB to the environmental impacts are shown in Figure S10.

To sum up, the environmental burdens of P-PCB are about two orders of magnitude less than O-PCB, as shown in Figure 5 and Table 4, which render an essential difference between P-PCB and O-PCB and that could be explained by the followings. Firstly, the raw materials of P-PCB are simple and environmental-friendly ones, of which more than 80% is cellulose paper and the environmental harmful materials only account for less than 5%. In contrast, the O-PCB has more unfriendly raw materials, such as epoxy resin, glassfiber, fillers and copper foils. Secondly, the pure additive method adopted in the P-PCB manufacture is more economical and simpler than the conventional processes of O-PCB production, which is energy consuming and sacrifices a large amount of copper. Thirdly, the waste treatment of P-PCB is more environmentally-friendly for its cellulose nature; whereas epoxy requires a high temperature of 800 °C to decompose, and toxic emissions such as dioxin could be discharged,[33] which is restricted by European Union (EU) because of its potential hazards to human health.[61]

Concluding Remark and Outlook

This article for the first time evaluates the feasibility of a pure additive process for fabricating an ECA based multilayer P-PCB. Through a detailed comparison with the typical O-PCB, we show that the basic characteristics of our P-PCB prototypes have reached a promising performance level for the mid-range and low-end electronic applications. Additionally, from the LCA results we found that the environmental impact index of P-PCB is about two orders of magnitude lower of that of O-PCB, indicating a promising prospect of P-PCB in the future green electronic market. This study may have answered the question which has been for long disscussed that how "green" the paper electronics technology can be.

Although the present technology is still a proof of concept, and the current performance characteristics can only meet the needs for low density and low frequency electronics, we believe that with the rapid development of materials science and technologies, there will be more appropriate candidate materials and techniques for P-PCB to meet further needs; for example, with the development of advanced paper materials (considering dielectric property, thermal conductivity, fire-resistance, moisture resistance, transparency and surface roughness etc.),[21, 58, 62-64] conductive materials (stability, electrical conductivity, and processability etc.),[65] and the fabrication techniques,[66, 67] the use of P-PCB in the high density and high performance integrated circuits applications is not impossible. What is more, if combined with some substrate materials with particular characteristics like stretchability[68] or weavability[69], the P-PCB would have even more impacts in the future electronics.

We have shown the advantages and disadvantages of paper electronics with the case study of P-PCB in this paper. With the key problems being solved for better performance and standardized production, paper electronics will soon find broad applications in future green electronics, such as wearable electronics, household appliances, small electronic gadgets, consumable electronics, and toys etc.

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† Electronic Supplementary Information (ESI) is also included. See DOI: 10.1039/b000000x/

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Graphical Abstract:

A multilayer printed circuit board (PCB) can be fabricated using commercially available printing paper, which shows comparable functionalities with the conventional organic PCBs but 100 times less environmental impact.