PCB Integration of Dye-sensitised Solar Cells for Low-cost Networked Embedded Systems

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***Abstract*—Wireless sensor networks are envisioned to make a large impact on how sensor data from physical phenomena can be utilized by millions of users on the Internet. However, one concern in deploying a large number of real-world physical sensors is that replacing spent batteries might not be feasible. One solution to this issue may involve energy harvesting technology, e.g. solar panels. Solar panels are currently relatively expensive because they require a time-consuming and therefore costly assembly process. As an alternative, this paper suggests a new approach to powering networked sensors: the direct integration of a solar cell onto the sensor nodes printed circuit board. This approach eliminates the need for manual assembly and the use of expensive connectors. This article presents test results and a feasibility analysis of the direct integration of a dye-sensitised solar cell onto a circuit board. Preliminary results indicate that this approach is feasible for networked sensors. The aim of this work is to develop a method for the assembly of complete systems, consisting of a printed circuit board, components, and power supply, using a single production process. The first steps towards this aim have been taken, and the authors believe that the proposed approach may be one enabling technology for future large-scale, low-cost wireless sensor networks.**

***Keywords*-Dye sensitised solar cells, energy harvesting, networked sensors, wireless sensor networks**

I. Introduction

A wireless sensor network (WSN) is composed of a large number of heterogeneous sensor nodes, or *sources*, that sense phenomena in the physical world [1]. A sensor network also includes one or several gateways, or *sinks*, which forward sensor data from nodes in the internal network to an external network [2]. Research on WSN technology originally focused on military applications, such as battlefield surveillance, land mine detection, and soldier monitoring [3]. Current wireless sensor network research is additionally motivated by an increasing number of civil usage scenarios, such as environmental and habitat monitoring, seismic and volcanic monitoring, structural monitoring, and industrial applications [4], [5].

Wireless sensors are expected to have a drastic impact on how measurements of the physical world will be presented to users on the Internet. A vision, in which Internet-connected wireless sensors are deployed in the vicinity of users, named *the Internet of Things* [6] is also projected to enhance both safety and quality of life for future generations. For this vision to be realized, a number of issues must be resolved. Three of these issues, addressed by this article, are:

- Reducing power consumption
- Enabling wireless power
- Lowering the cost of the sensor nodes

Reducing power consumption can be achieved using a number of methods, such as using more efficient components, integrating more intelligent routing protocols [7], or developing energy-aware computing. Wireless power requires power harvesting, power storage, and an appropriate power usage architecture at the sensor node; see for example [8], [9], [10]. A node's cost will be reduced with the use of more integrated components, and the price of printed circuit boards (PCB), integrated circuits (ICs), and other components will drastically decrease with increased production volumes. However, the costs of certain node components, such

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as batteries and power supplies, do not scale as effectively as circuit board production volumes. The cost of packaging a complete node with a circuit board, batteries, solar panels, and enclosure will not be reduced by the same order of magnitude as that of the electronics. This is a major obstacle for realizing the vision of massive wireless sensor networks.

One consideration for energy harvesting relates to the energy density from different sources. It is clear that solar cells are superior to other energy harvesting approaches such as vibrations and thermoelectric power, as reported by Yang et. al [8]. Therefore, the focus of our work was to investigate direct, low-cost solar cell technology integration with a sensor node.

When comparing different solar cell technologies, both power efficiency and cost must be considered. Two main candidate technologies: silicon based solar cells and dye sensitised solar cells (DSC), sometimes called Grätzel cells [11], have been selected for further investigation. A comparison between silicon based solar cells and DSC can be found in [12]. Regarding energy capability a traditional silicon-based solar cell offers about $43mA/cm^2$ at 0.7V, whereas current DSCs offer about $22mA/cm^2$ at about 0.6V [13]. Regarding cost, DSCs are considered superior because material cost and manufacturing cost is clearly lower than for silicon-based cells.

This paper presents a novel approach aimed at further reducing manufacturing and integration cost for DSCs that power wireless sensor nodes. The approach is to manufacture a solar panel directly on a sensor node's circuit board, thus reducing the cost of manufacturing the cell separately and eliminating the assembly cost. This has several benefits, as the resulting device consists of an integrated solution that effectively eliminates costly silicon-based cells, cables and connectors, and an additional integration step. The proposed approach also increases the system's robustness because there are no connectors or cables that can disconnect due to mechanical phenomena, e.g., vibrations or impacts. The goal of this research is to develop a holistic method for producing complete low-power systems, where assembly of the PCB, components, and an energy-harvesting device can be completed with a single process. The first steps have been taken - a solar cell has been integrated with a PCB - and the authors believe that, in the future, a solar cell will be directly printable on a PCB using a sequential build-up (SBU) technique. For example, Blackshear et al. reported in 2005 [14] the advantages of using SBU for chip assembly onto circuit boards.

The paper is outlined as follows: this section has presented related work and a background of wireless sensor networks and solar cell technologies. The next section gives an overview of DSCs. Section III presents the new method of integrating a DSC directly onto a circuit board, and Sections IV and V show the experimental setup, and results from real-world tests, respectively. Finally, suggestions for future work are presented in Section VI, followed by conclusions in Section VII.

II. Dye sensitised solar cells

The dye sensitised solar cell (DSC) is currently being investigated as a low cost method of harvesting the abundant energy of sunlight into electricity [11]. It offers the advantages of low cost and better light harvesting in low and/or diffuse lighting, which are more realistic conditions than would be optimal for other photovoltaic devices, such as silicon-based cells.

The DSC operates by light exciting an electron in a dye molecule adsorbed onto a mesoporous semiconductor to an energy level above the conduction band of the semiconductor. The electron is quickly transferred to the conduction band of the semiconductor and transported through the network of interconnected nanoparticles to the electrode. The electron passes through the external circuit and then reduces an electrolyte at the counter electrode which in turn reduces the dye, returning it to its ground state. This type of solar cell exhibits an efficiency of over 11 %, as shown by Han et. al [15]. The operation of the DSC allows for cheap, abundant materials to be used for device components, combined with less energy-intensive processes used for manufacturing. This offers the potential for significantly lower production costs compared to more traditional silicon solar cells, in turn reducing the energy and cost payback times significantly. These factors make the DSC an attractive renewable energy source for the future.

The drawbacks for DSCs are related to lower performance compared to silicon devices, a corrosive electrolyte that limits material selection options and shorter device lifetimes, primarily due to the volatile electrolyte used in the most efficient designs. It is difficult to construct devices with long lifetimes when encapsulating a volatile, corrosive solvent. To this end alternative electrolytes have been investigated - generally highly viscous, non-volatile ionic liquids. Solid state hole conductors have also been considered and are a more elegant solution, as they also remove corrosive iodine from the system, expanding materials selection options within the cell as well as eliminating any solvent leakage issues. The leading organic hole conductor is 2,2,7,7-tetrakis(N,N-di-p-methoxypheny-amine)-9,9-spirobifluorene (spiro-MeOTAD) [16], with reported device efficiencies up to 4.4% [17]. A solid state device is typically constructed onto fluorine doped tin oxide (FTO) glass with a titania (TiO_2) layer coated on top, which is dyed and then infiltrated with the hole conductor. The counter electrode is a gold layer evaporated onto the coated titania layer and connected to an electrically isolated section of the FTO glass. This architecture is ideal for integration with circuit boards, shown in Fig. 1. The circuit board may be physically contacted to the gold contacts on the back of the DSC module, as shown in Fig. 3. The connections will be made such that each cell is independently measurable and bi-passable if necessary.

III. PCB WITH INTEGRATED DYE SENSITISED SOLAR CELL

DSC modules were created using the screen printing technique, on pre-etched 100 mm × 100 mm 13 Ω/square FTO coated conducting glass (Nippon) masterplates. The etching to separate the contacts for the individual cells was performed using a laser engraving system, a Versa laser VL3.50 unit, which produced fine lines (~150μm) with high spacial precision. Following this procedure the glass was cleaned and a dense blocking layer of TiO_2 was deposited by spray pyrolysis, with the areas for electrical contacts by solder and the gold layer being masked by flattened aluminium rods.

The screen printing paste for the active layer, provided by JGC Catalysts and Chemicals Ltd,

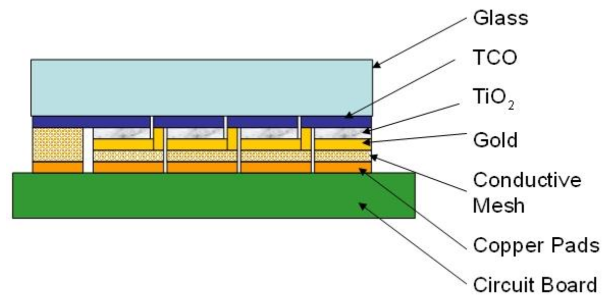

Fig. 1. Layout of the PCB with integrated dye-sensitised solar cell

contained 18 nm particles of anatase titania and was diluted by terpineol at a ratio of 2:1 paste (Fluka). The thickness of the titania layer was determined by a Veeco Detak 150 stylus profilometer, to be ~2 μm. The titania layer was incrementally heated to 450°C for 30 min and then to 500°C for 15 min. The master plates were cut into 50 mm × 50 mm modules and reheated to 500°C for 30 mins before being placed into the dye solution of 30 mM Z907 (Dyesol) in an acetonitrile/tert-butanol 1:1 mixture. for approximately 24 hours. The electrolyte was a solid state hole conductor, namely Spiro-MeOTAD, which was deposited by spin-coating using a solution that consisted of 180mg/mL of Spiro-MeOTAD (Merck) in chlorobenzene (Sigma) with additives of 4-tertbutylpyridine (TBP) (Sigma) (17.6ul/mL) and Li-TFSI (Sigma) (19.5mM). Chlorobenzene was used on a cotton bud to remove excess Spiro-MeOTAD from the glass were series interconnects were to be formed. The gold charge collecting layer was deposited onto the module via thermal evaporation, and the areas not to be coated with gold were masked with Kapton tape^{TM} (3M).

An attempt was made to integrate these devices onto a PCB using conductive epoxy however, this had a detrimental effect on the DSC leading to dye desorption. Therefore, this approach was abandoned in favour of using a soft compressible conductor. The material used was a polymer mesh substrate with copper deposited onto it. The copper mesh was cut into pieces of the same width as the pads, but slightly longer such that they could be laid over the pads and adhered using Kapton tape. The module was placed on top of the PCB such that the gold contacted the copper mesh and no shorting occurred between cells. The PCB and DSC module where

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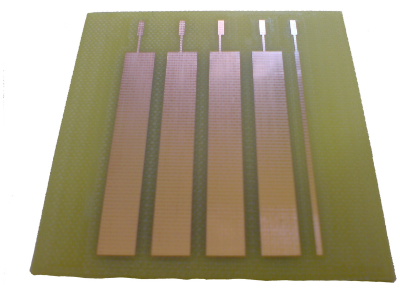

Fig. 2. Prototype board layout

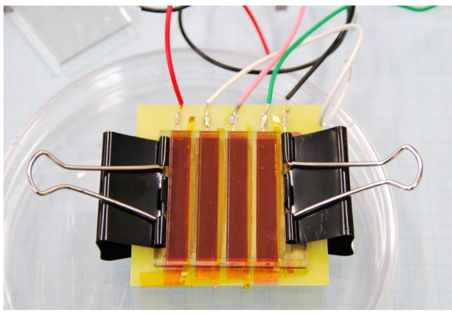

Fig. 3. PCB DSC solar panel prototype board, ready for integration with sensor node

then clipped into place using bulldog clips. During these alignment and clipping processes care was taken not to damage the fragile gold layer. Wires were soldered onto the board such that the entire module could be used or individual cells could be measured and/or bypassed if faulty. Fig. 2 shows the PCB that serves as the base for the new solar cell. The board, which is composed of four copper stripes each 49 mm wide and 6 mm long, was manufactured using a milling machine from an Eagle CAD design.

Fig. 3 shows a board produced with a DSC on a PCB. This board was used for initial tests and for 5-month degradation tests.

IV. Experimental setup

Several experiments were performed to investigate the performance of the PCB-based cell. To evaluate the performance of the module under standard conditions a solar simulator was used. The modules were tested under 1 Sun illumination, 100 $mWcm^{-2}$ AM1.5G, using a 1000 W solar simulator xenon lamp (Oriel) fitted with an appropriate filter to achieve spectral match and a Keithley 2400 source meter. Illumination intensity was varied by the use of fine wire mesh and calibrated using a silicon diode. The active area was 10.5 cm^2, while the size of the glass was 25 cm^2, this shows a poor active area to device area ratio. In future work this will be increased with 80% coverage, which is a challenging, but achievable, target for an interconnected module of this size. No masking was used; efficiencies may therefore be over estimated due to light piping within the glass.

To investigate the real world performance and feasibility for practical use, tests were performed both indoors and outdoors using different light sources.

A. Measurement system

A measurement system was created to capture characterization measurements for the PCB solar cell. The measurement system, shown in Fig. 4, consists of a 24-bit analog-to-digital converter (ADC) that measures the voltage drop over a 5 ohm resistor, which is used to measure current. To obtain an I-V curve, a digitally programmable potentiometer was also used so that different loads could be presented to the cell. A Mulle v3.1 networked sensor node equipped with a Bluetooth 2.0 transceiver was connected to the measurement system. Using this approach, the PCB cell can be tested outdoors by having a wireless connection to a laptop or PC, which can be placed indoors. The measurement system will be used also to measure the temperature dependency of the cell during winter tests. In addition, the measurement system also serves as a building block in the power supply unit (PSU) that may be used together with the PCB-cell. The PSU includes a boost converter that generates a 5.0V output used to charge a super capacitor. A switch is used to select whether the Mulle should be powered by the super capacitor or by a battery. The Mulle v3.1 also features a battery monitor chip, capable of measuring battery voltage, power consumption, available energy, and estimated lifetime. Combined with the Mulle's on-board features, the PSU can enable true energy- and power-aware operation.

Fig. 5 shows the measurement system. The system can measure voltages up to 6.5V, and current with a resolution around 20μA. The load can be programmed to any value between 100Ω and 100kΩ in 256 steps.

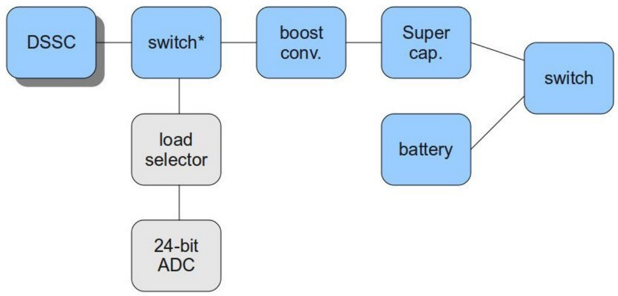

Fig. 4. Measurement system overview

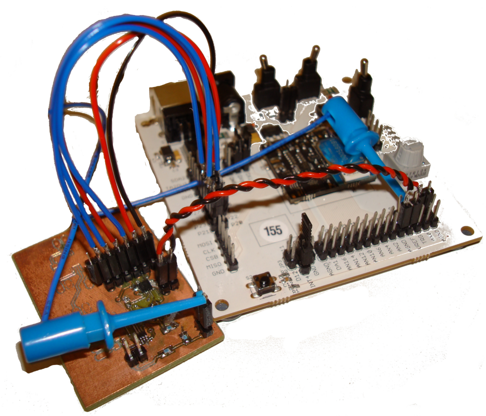

Fig. 5. Measurement system implementation

The measurement system is completely wireless, which allows remote monitoring of the PCB cell. A dedicated software written in C was used to retrieve data from the Mulle and store the results to file. In future implementations, the measurement system should also be integrated with the solar panel to enable true energy- and power-aware sensor node operation. By measuring available stored energy, power harvesting output and power usage, the software can be used to make intelligent decisions regarding how energy-consuming tasks should be managed.

B. Performed measurements

The following experiments were performed in order to test the cell's performance under in a real-world setting. The different tests that the cell was tested in are typical application locations where a networked embedded system can be deployed.

1) Measurement of the PCB DSC module's performance initially and after 5 months

TABLE I
MULLE V3.1 POWER CONSUMPTION

Mode	Delay	Current
All systems sleep	-	0.004 mA
MCU 10.0 MHz, BT off	-	7.6 ma
MCU 5.0 MHz, BT off	-	5.1 mA
MCU 2.5 MHz, BT off	-	3.1 mA
MCU 1.25 MHz, BT off	-	2.2 mA
MCU sleep, BT listen	2-12 s.	1.0 mA
MCU sleep, BT active	-	40.3 mA
MCU sleep, BT sniff (210 slots)	131 ms.	8.4 mA
MCU sleep, BT sniff (2010 slots)	1256 ms.	2.8 mA
MCU sleep, BT parked (18 slots)	13 ms.	7.5 mA
MCU sleep, BT parked (200 slots)	130 ms.	2.7 mA
MCU sleep, BT parked (4094 slots)	2560 ms.	1.8 ma

2) Measurement of the PCB DSC's current response at various light incident angles
3) Measurement of the effect of varying light intensity on the current output of the PCB DSC module.
4) Tests of power generation at indoor and outdoor locations and different lighting conditions

The cell was tested for long term degradation effects and different light sources at different angles. However, no temperature tests were performed. It is considered as future work to investigate the cell's performance in low temperature environments.

C. Real-world energy usage

The feasibility of using the prototype solar cell, with the power characteristics presented in the previous section, for a real-world networked sensor is presented here. The Mulle node [18] has been used in a number of WSN and BSN applications [19], which will be used as an example for calculating operational lifetimes when combined with the PCB cell. Table I shows examples of the current consumption of a Mulle v3.1 in different operating modes.

V. RESULTS

The initial performance of the PCB DSC module was 1.47% efficient initially, degrading to approximately 1% after 5 months, as shown in Fig. 6. The aging of the module was performed with no encapsulation and at ambient conditions. The drop in performance is due to reduced current most likely caused by the degradation of the dye molecules by

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oxygen and water. This suggests good stability and may be significantly improved with encapsulation of the device. Figure 7 shows the performance of the PCB DSC at varying incident light angles. Here 0° corresponds to the light beam being perpendicular to the surface of the module. The module demonstrates good performance with the PCB DSC maintaining 80% of current at a 45° tilt. Figure 8 shows the variation of the output current with varied input light intensity, which remains linear for lower light intensities, but slightly decreases upon approaching full illumination, showing the cell is approaching it's photocurrent limit. This data may help determine the illumination intensity from the photocurrent produced by the module although this will exhibit a significant spectral mismatch for artificial light sources.

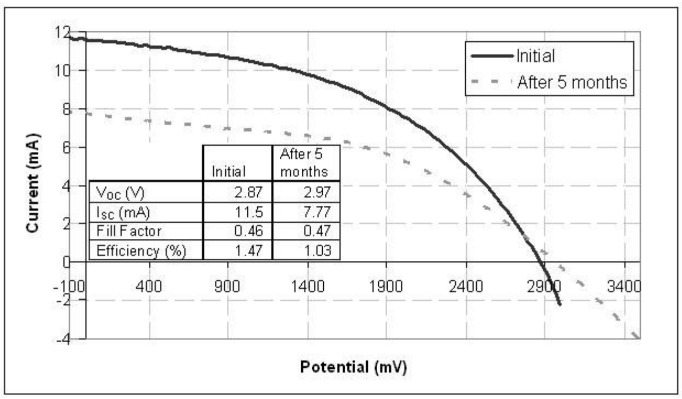

Fig. 6. PCB DSC current-voltage performance, initially and after 5 months

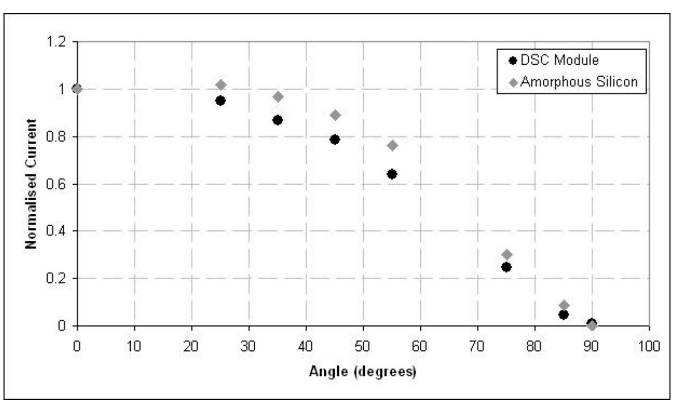

Fig. 7. PCB DSC short circuit current response for different light incident angles

To evaluate the module's output in real world

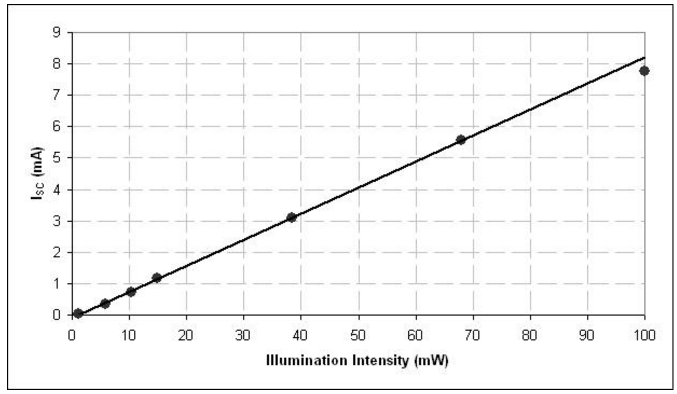

Fig. 8. Short circuit current response for the PCB DSC with light intensity varying between 1 and 100%

scenarios the short circuit current was measured at a number of locations that reflect typical applications for the sensor node which can be placed either outdoors or indoors. The following locations were tested:

i) Office with ceiling fluorescence lightning and ambient light from shaded windows; cell horizontal
ii) Corridor with ceiling fluorescence lightning and no ambient light from windows, cell horizontal
iii) Workshop well lit with with ceiling fluorescence lightning and some ambient light from shaded windows; cell horizontal
iv) Office desk with 23W desk fluorescent lamp; cell horizontal
v) Near a closed window with no direct sunlight; cell horizontal
vi) Near an open window with no direct sunlight; cell horizontal
vii) Near a closed window with some direct sunlight; cell horizontal
viii) Near a closed window with direct sunlight; cell horizontal
ix) Near a closed window with no direct sunlight; cell tilted for maximum illumination
x) Outside in full sun light; cell horizontal
xi) Outside in full sun light; cell tilted for maximum illumination

The resulting data is in Table II. For a number of practical usage scenarios assuming no real-time radio communication, a small dye solar cell should be sufficient to provide the necessary power for making wireless power a reality.

TABLE II
CURRENTS FROM PCB DYE SOLAR CELL IN TYPICAL USAGE SCENARIO LOCATIONS.

Location	distance to source [m]	Current [μA]
i	2	6
i	0.3	60
i	0.1	220
ii	1	6
ii	0.1	90
iii	2	50
iv	0.2	240
iv	0.01	3000
v	-	220
vi	-	330
vii	-	800
vii	-	2650
ix	-	3700
x	-	6800
xi	-	8000

When comparing the power output from the PCB DSC cell with Table I, it is clear that the generated power is sufficient for powering a Mulle sensor node as long as low-power modes are utilized. Since the peak power of a Mulle is higher than the maximum power output of the PCB DSC cell, some storage will always be required. A super capacitor, a rechargeable battery, or a combination of both can be used for energy storage. Performed tests indicates that the presented approach is feasible for powering low-power electronics such as sensor nodes.

VI. FUTURE WORK

The first steps towards an integrated manufacturing process for solar-powered embedded systems have been successfully completed. In the next step, the authors will continue to investigate printing a dye sensitised solar cell directly onto a printed circuit board using mass production techniques. The ultimate aim is to develop a method for assembling and manufacturing a complete system that includes a PCB, components, and a solar cell, using a single process.

Another performance-enhancing approach worth investigating requires interconnecting a number of cells in a matrix-style framework using MOSFET transistors. This is possible because all connections can be made by vias, instead of wires. This would enable the system to identify cells with bad performance, and to allow them to be bypassed. The system would thereby dynamically reconfigure itself for maximum performance depending on: light irradiation, work load, and properties of the cells. This approach requires software-support for full performance advantages.

Another issue that needs further investigation is how the system should be encapsulated in a transparent package. One method is the embed the entire system in optically transparent glue, as shown in [20]. How low temperatures are affecting the cell's performance must also be investigated. Finally, the use of a more low powered device, such as the Mulle v5.2 with an IEEE 802.15.4 radio, should be used to test the true performance in a wireless sensor network.

VII. CONCLUSION

This paper has presented a novel approach for powering low-power electronic devices, such as networked embedded systems and sensor nodes. The approach integrates a dye sensitised solar cell directly onto a device's circuit board thereby reducing the material and assembly costs. A prototype device has been manufactured to demonstrate the feasibility of this approach and to enable the cells' real-world performance to be evaluated. Test results, both initial and after five months of degradation, have been presented to support the claims.

By integrating the power supply directly onto a circuit board, the authors envision that networked sensors may be manufactured at a greatly reduced cost in the future. When combined with new technologies for energy storage and transparent encapsulation, the presented approach can be an enabling technology for future low-cost, large-scale wireless sensor networks, in support of the vision of *the Internet of Things*.

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