Prospects for implantable sensors powered by near infrared rechargeable batteries

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Many useful computing, networking and sensing devices could be implanted inside the body if they could only be reliably powered. At the University of Kentucky, our group is looking at spectrometric sensors for the determination of blood alcohol content (BAC). Cardiac pacemakers now in use are powered using lithium primary batteries with a lifetime between five and ten years.[1] Electromagnetic power can be delivered through skin,[2,3] allowing implanted devices to be powered indefinitely. However, such a scheme requires an external transmitting device to deliver EM energy continuously, or to recharge a battery. A novel power supply for implantable biosensors has been described by Goto *et al.*[4] In this power supply, near infrared (NIR) light transmission recharges a lithium secondary battery wirelessly through the skin. The sun is a good source of NIR light, and its use requires no other external device to deliver energy to the recharging system. A photovoltaic cell array implanted beneath the skin can receive NIR light through the skin, and charge the battery that is directly powering an implanted biosensor (see Figure 1).

Lithium batteries supply steady output voltage through their lifetime because of their specific electrode potentials. Rechargeable lithium batteries demonstrate superb charge/discharge characteristics that can meet the power requirement of operating implants for a long duration.

In the implantable power source, the current produced at the photodiode is supplied to a rechargeable battery and to an implanted sensor connected to the battery. In this manner, the battery is charged and is able to automatically power the device when the photodiode array is not illuminated. The current flow backward from the battery to the photodiode array is shut off by inserting a diode between them.

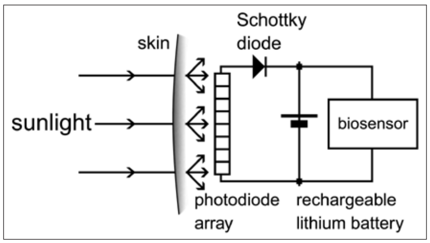

Figure 1. NIR light penetrates skin sufficiently to recharge a battery powering an implant.

Of course, sunlight is not always available. One light source easily able to recharge the battery in the absence of sunlight is a NIR laser diode (e.g., a Coherent S-81–1000C-100-H at 810 nm). The photodiode array to convert light into electricity comprises eight Si PIN photodiodes (Hamamatsu, S6775) connected in series to obtain sufficient voltage to the charge the battery. The detection area for every photodiode is 5.5 × 4.8 mm. The dimensions of the complete photodiode array prototype, including the packages, are 28 × 20 × 3 mm. The battery is a composite dimensional manganese oxide (CDMO) lithium secondary battery (Sanyo, ML-2430, 100 mAh).

The power conversion efficiency of the photodiode array varies with the voltage across it. The photodiode array sustains the best power conversion efficiency throughout the battery charge because the voltage across the photodiode array is regulated by the battery. Enhanced power conversion efficiency can be used to provide shorter charge time or reduced radiant power, or both.

Animal studies have been conducted with the photodiode array completely implanted under the shaved abdominal skin of an anesthetised rat at 10 weeks of age. The pathlength of the rat skin over the photodiode array was 0.8 mm (see Figure 2).[4]

In battery charging tests, the photodiode array, the Schottky diode, the battery and a commercial cardiac pacemaker (as a test load) were connected as detailed in Figure 1. The initial voltage of the battery was 2.74 V. The same battery was employed throughout the experiments, even though its initial voltage for each measurement varied because of successive charging and discharging. During the battery charge tests, the battery voltage and the current flowing from the photodiode array were measured. According to the I–V curves, conversion efficiencies of 16–21% can be attained when the photodiode array voltage ranges between 2.8 V and 3.3 V, which was consistent with a battery voltage of 2.5–3.0 V for a Schottky diode voltage of 0.3 V. For 5.4 and 20 mW cm^{-2}, the maximum power conversion efficiencies were 19% and 21%, in that order. The transmittance of the rat skin was determined to be 64%.

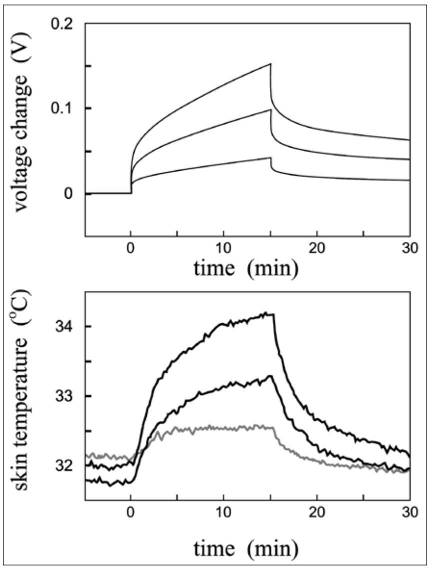

Figure 2. Charging the battery slightly elevates skin surface temperature. Device illumination begins and ends at 0 and 15 min, respectively.

The power conversion efficiencies of the photodiode array were approximately 20%. Figure 2 shows the time-course of the battery voltage change and the skin temperature. The charging current was almost unvarying during laser illumination of the skin. The voltage rise all through the battery charging process resulted from the rising charge accumulated in the battery and from its internal resistance, into which the current was introduced. Injection of current into the internal resistance leads to the rapid voltage increase and reduction at the start and the finish of the battery charge, respectively. The skin temperature appears to saturate within the duration of the battery charging, though, for higher power densities, more time was needed for the temperature to saturate.

The current necessary to charge the battery controlled how much power the photodiode array was asked to collect.

The temperature increase at the irradiated region constrained the incident power density. The heat created from light absorption by the photodiode array was actually much greater than that by the skin. At the same wavelength and power density, the temperature increase for the rat skin without a subsurface photodiode array was as low as 0.2°C. Given that the heat produced at the photodiode array governed the skin temperature, it was probable that the power incident on the skin was limited by how much power was collected by the photodiode array, but not by how much power was absorbed by the skin. The incident power limit could also be set by the safety of the photonic power to tissues over extended periods, independent of the temperature increase at the skin (e.g., the incident illumination could be a cause for concern when UV wavelengths are included, as they are in sunlight).

Increasing the detection area of the photodiode array, rather than by increasing the incident power density, also increases the charging current. Sunlight provides 100 mW cm^{-2}, enough for battery charging, but optical filters may be necessary in order to reduce unwanted power that generates too much heat at the photodiode array, or exposes the skin surface to excess unwanted UV light. For practical use, NIR light-emitting diodes can be good alternative light sources when needed. For an incident power density of 22 mW cm^{-2}, 17 min of illumination at 810 nm wavelength was sufficient to charge a battery powering a pacemaker (a stand-in load for the biosensor). Charging time was set by the current the photodiode array generated. The temperature rise at the illuminated skin was 1.4°C at this power density. The dominant cause of the temperature rise was the photothermal effect at the photodiode array. For a human skin 2 mm thick, a photodiode array with a 10 cm^2 detection area should give the same charge performance as mentioned above with much less temperature rise.

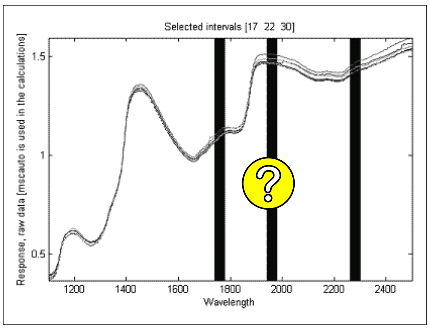

Figure 3. Wavelength bands that correlated to BAC in the skin of one subject ($r = 0.90$, $RMSECV = 0.00634$).

Ethanol sensor

Current alcohol sensors (e.g., breathalyser technologies) do not collect enough data at the right times to be truly useful therapeutically. The alcohol sensors in current use are mostly based on indirect evaluations of alcohol content, and have all been proved to be deficient in several key areas, such as:

- the self-reporting method, for example, has questionable validity, poor temporal resolution; minimal quantification;
- breath sensors disrupt ongoing activity, have poor time resolution—limited by the time required to obtain adequate breath sample, a bulky and obtrusive apparatus;
- wrist-worn alcohol-diffusion measurement devices have skin irritation issues, calibration issues associated with placement and back diffusion of alcohol, latency of measurement and compliance;
- blood and urine samples have poor temporal resolution and are too obtrusive; and
- MRI studies are too expensive, obtrusive and have poor temporal resolution.

A means of remotely measuring blood alcohol surreptitiously, or unobtrusively using an implant, is needed to monitor alcohol in humans in their natural living environment to study how they naturally use and interact with ethanol. Knowing blood alcohol levels at the right times is necessary to evaluate pharmacotherapy or other therapies. For this reason, our group is looking at powering NIR-based sensor implants.

Pulsed NIR diode light sources in implants can be designed to operate within the power supply parameters set by the Si PIN photodiodes and Li battery. In a single subject, a relatively small number of wavelength bands (e.g., three) (see Figure 3) often correlate well to BAC. A small, customised implant using diodes that emit in these bands and powered by the NIR rechargeable battery system offers one approach to solving the problems described above with more traditional measurement systems. The results of such studies will be reported in upcoming publications.

Acknowledgements

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