Optical Methods for Wireless Implantable Sensing Platforms

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ABSTRACT

Ultra small scale implants have gained lots of importance for both acute and chronic applications. Optical techniques hold the key to miniaturizing these devices to long sought sub-mm scale. This will lead towards long term use of these devices for medically relevant applications. It can also allow using multiple of these devices at the same time and forming a true body area network of sensors. In this paper, we present optical power transfer to such devices and the techniques to harness this power for different applications, for example high voltage or high current applications. We also present methods for wireless data transfer from such implants.

Keywords: Implant, Sensors, Wireless, Optical, Photovoltaic

1. INTRODUCTION

Application of microelectronics to medicine is being considered as a revolution in the field of biomedical engineering [1]. The use of implants has been increasing in general. The advent of smart and ultra-small (sub-mm) implants can bring an entirely new type of health care system as well as in biomedical research and diagnostics.

Miniaturization of the functional implants holds the key to fully utilize these devices in terms of long term usage. An important step in this miniaturization is utilizing wireless techniques for powering and communication. RF and inductive methods have been applied before but pose a fundamental size limitation on such systems and also pose problems of electrical isolation for sensitive signal measurements. Hence, optical methods are very attractive for these applications. Photovoltaic power harvesting systems can be smaller in size and can be designed using the same technology used in microelectronics to design integrated circuits. Similarly, optical communication can provide much higher data rates with much smaller footprint than electrical methods. To the best of our knowledge, this work is the first demonstration of an integrated CMOS based power harvesting system and an ultra-small laser on the same platform. This depicts the possibility of using fully wireless optical methods which leads towards extreme miniaturization of these systems.

1.1 Design Aspects

The most important realization in designing ultra-small (sub-mm) scale implantable devices is that the footprint for all subsystems system should be minimized. For power harvesting subsystem, this means that high energy focused beams have to be used to transfer power to the system. Optical beams have the attractive property of being able to focus to micron scale resolution. Next important design consideration is then to be able to absorb most of this energy. This calls for use of efficient photovoltaic absorbers on chip. At the same time, the cost of the system and integration call for using integrated photovoltaic systems which use the same materials as used in integrated electronic fabrication. This is by far silicon although other materials (e.g. germanium and compound semiconductor materials) are also increasing in popularity. Silicon based CMOS electronics is the industry standard for ultra-small integrated electronics. For implants, this technology can minimize the footprint of on-chip control and processing circuitry and hence is the technology of choice for our applications.

Silicon is an indirect bandgap material with bandgap energy of 1.1 eV. It can absorb photons of 1.1 μm and smaller wavelengths. The penetration depth of light in visible and infra-red region is shown in figure 1 [2]
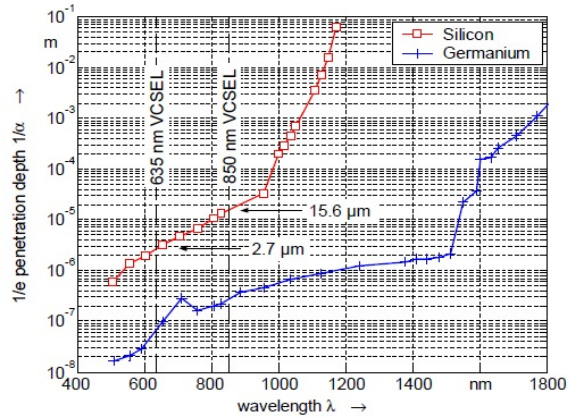
Fig. 1 Penetration depth of Si and Ge as a function of wavelength

The absorption depth of light in silicon is dependent upon wavelength. For the infrared region, the absorption depth is in the order of few microns to few 10's of microns. The wavelength selection criterion is based upon minimizing absorption in the skin and tissue, and maximizing absorption in the photovoltaic without heating either of these. The Infra-red region is very suitable for such applications due to the presence of a region of low tissue absorption which overlaps with suitable wavelengths which can be absorbed in silicon photovoltaic devices without creating lots of phonons and heating the silicon substrate. For reference, absorption of light in infra-red region in human skin is shown in figure 2 [3]
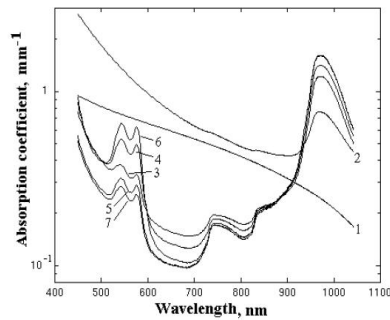

Fig. 2 Wavelength-dependent absorption of different components of human skin (1-stratum corneum,2-living epidermis, 3-papillary dermis,4-upper blood net dermis,5-reticular dermis,6-deep blood net dermis and 7-subcutaneous fat)

Absorption is not the only criterion for this application. Scattering is another important consideration. Scattering depends upon wavelength. Scattering in tissue layers near surface in near infra-red region is shown in figure 3 [4]. It is evident that scattering increases with a decrease in wavelength but is pretty constant in the range of 750nm to 1000nm. Hence, this window is quite suitable in terms of minimal scattering as well.
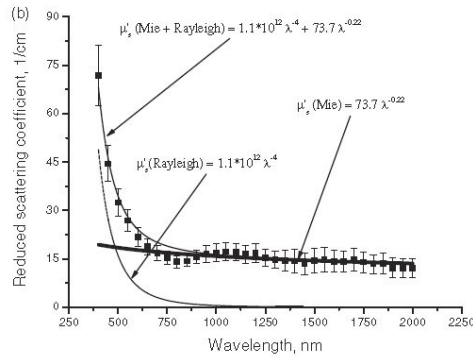
Fig. 3 Scattering coefficients of different layers of the skin tissue, and fitting results from Mie and Rayleigh theories (the spectral dependence of reduced scattering coefficient μ_s of human skin *in vitro* and its approximation by power law.)

Reflectance is also another important aspect. It depends upon skin type and is shown in following figure 4 [5]. It shows that reflectance is less variable in the infra-red region around 800nm. This can further be reduced by using index matching substances between skin and the device.
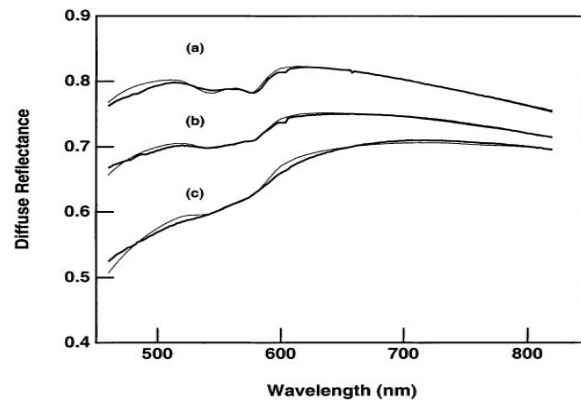

Fig. 4 Reflectance as a function of wavelength in skin (a) White Caucasian (b) Japanese and (c) black African

The optical communication link is used to communicate information form the sensor to an outside reader. This system uses same optical wavelength window as the optical powering system. However, the exact wavelengths used are spaced apart from each other to minimize the cross talk between the two types of signals since these are located in close proximity to each other due to the very small size of the whole device. We demonstrated the concept using a Vertical Cavity Surface Emitting Laser (VCSEL) from ULM Photonics. These devices have very small threshold current and one of the smallest threshold voltages for devices which emit in the desired wavelength range. Also, these have much smaller thermal loss compared to micro LEDs.

2. SYSTEM DESIGN

The whole system comprised of CMOS electronics and sensing units, optical powering and optical communication systems. Optical powering setup was used to power the CMOS and/or the optical communication link. The VCSEL was connected to the photovoltaic device through either external electrical connection or on-chip wire bonds.

The integrated photovoltaic devices are designed according to design requirements for special applications. One such example is the design to generate high voltages (in excess of 1 V) using standard CMOS which has a shared substrate

between the photovoltiacs and electronics. This leads to several design challenges. Another application is high current requirement while providing moderate voltages.

The design of these devices was done using TSMC 250 nm standard CMOS technology. Additional designs were done in ST 130nm Silicon-on-Insulator based CMOS technology.

The type and quality of a p-n junction also controls the output of the photovoltaic devices. The types of junctions are both lateral and vertical in standard CMOS and only lateral in SOI CMOS. For a standard CMOS process with deep n-well regions, different types of doped regions are available to act as parts of photovoltaic cells. These are shown in figure 4.
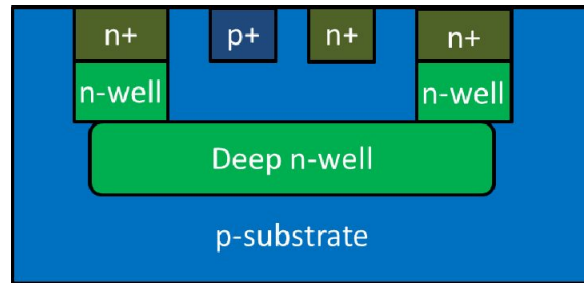

Fig. 4 Schematic layout of the CMOS photovoltaics

The open circuit voltage of a p-n junction photovoltaic device is given by following relationship

$$V_{oc}=(nkT/q)\ln(I_{sc}/I_o + 1)$$

Here, I_{sc} is short circuit current which in this case is equivalent to photogenerated current and I_o is the reverse saturation current.

This shows that to maximize this voltage, high light intensities are required to generate large number of photogenerated carriers (photo current) while having very low reverse saturation current.

The short circuit current of a p-n junction photovoltaic device is given by following relationship

$$I_{sc}=qGA(L_n+L_p+W_d)$$

The main design consideration in these implementations is maximizing the region where photons are absorbed and resulting electron-hole pair can be collected efficiently without being absorbed again in the material. This region includes the depletion region of the p-n junction devices (W_d) as well as diffusion length of minority carriers in p (L_p) and n (L_n) regions and the area of the photovoltaic cell (A) and G is the rate of photgenerated electron-hole pair.

For a loaded photovoltaic device which has maximum capacity to generate photo current I_{sc}, only a portion of it can be provided to a load for a non-zero voltage V_{loaded} across the device. This is depicted by following equation.

$$V_{loaded}=(kT/q) \ln [(I_{sc}-I_{load})/I_o+1]$$

Even higher voltages can be generated by connecting two or more devices in series. This is quite straightforward in SOI based CMOS due to inherent isolation available between all the devices. However, for standard CMOS, since the substrate is shared among the devices, this is more complicated. There are different topologies and methods reported in literature [6, 7] to achieve high voltage for different applications. In this work, we present a topology designed using equivalent circuit of deep n-well based structures and special contact schemes. This eliminates the need of extra DC/DC converter circuitry to generate higher voltages. This resulted in highest reported open circuit voltage of 1.5 V using CMOS which hasn't been achieved before. The contact structure and equivalent circuit representation is shown in figure 5.
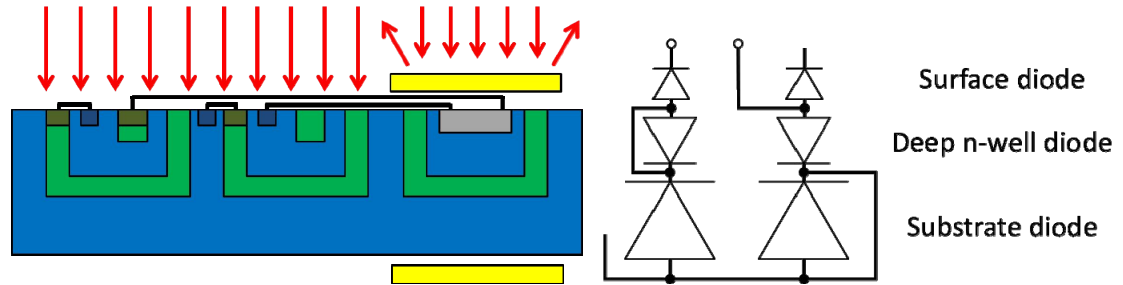
Fig. 5 (A) Connection Diagram and (B) Equivalent Diode circuit of two CMOS photovoltaic cells connected in series to generate series connected devices for higher voltage (same color coding as fig. 4. Yellow solid represent metal shielding of CMOS circuit)

For a given design, the total area of the photovoltaic device is fixed due to design constraints on the size of the device. Hence, maximizing photogenerated current is achieved by maximizing the absorption region of the device. This includes depletion region and minority carrier diffusion length in both regions (n and p regions). For vertical devices, substrate diode structures can generate much higher currents than shallower surface diodes. For lateral devices, lesser doped regions (n and p) can generate higher currents than highly doped (n+ and p+) regions due to larger diffusion lengths and hence larger photogenerated current which can be collected at device terminals. Another important constraint is to have ohmic contacts within the diffusion length of a junction region to be able to collect most of the photogenerated carriers without these recombining. Thin metal contacts (lower level metals in CMOS process) are used for this purpose to maximize the photogeneration of carriers as well as collecting these to be able to flow through external device terminals. This is shown in following figure of the CMOS die.
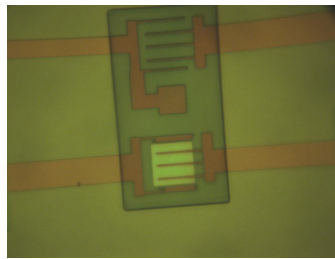

Fig. 6 Micrograph of tape-out CMOS photovoltaics utilizing deep n-well based devices

For comparison, compound semiconductor based micron-scale commercial modules were also used as photovoltaic devices. GaAs based PV modules from ULM were used for this purpose.

Vertical Cavity Surface Emitting Lasers (VCSEL) are smallest lasers and hence are attractive sources for optical communication from implants. These can be further miniaturized by thinning down the substrate. In addition to mechanical polishing, the substrate can be etched away with a piranha solution of $H_2SO_4 : H_2O_2 : H_2O = 4 : 1 : 1$ while the front side was protected with wax. The etch rate was determined to be ~1 μm/min. This thinning process facilitates subsequent bonding and fabrication steps since the device surface would be much flatter.
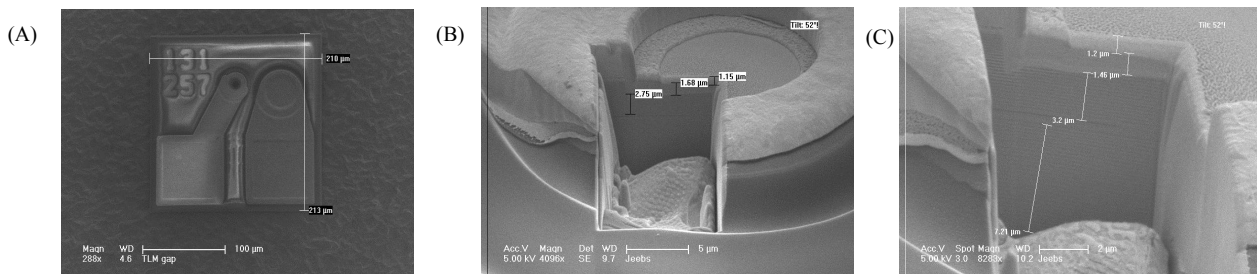

Fig. 7 (A) SEM image of a VCSEL chip after etching;   (B) Cross section of the device   (C) Cross section w/ VCSEL mirror structure

3. TEST SETUP

The setup used to optically test these devices consist of a high power IR laser (0.8W), a Keithley Source Meter and an optical table setup for alignment. A semiconductor parameter analyzer on an electrical probe station was used to do electrical testing of the devices first. The optical testing was carried out by using an electrical probe station and an optical test setup to guide the laser to be focused on the chip. The chip output was measured using both the source meter and a high precision digital multimeter. Different sized resistors were used as a load to measure the load curve. Alternatively, this was done using the source meter to sink a definite magnitude of current from the photovoltaic device and measuring the corresponding cell voltage.

Similar testing scheme was used for testing the VCSEL. It was glued to the CMOS substrate using insulating glue. Wire-bonding was used to make electrical connections to it. A semiconductor parameter analyzer was used to run a voltage sweep on the VCSEL to measure its response parameters. The result is shown in following figure

We used an external signal generator to generate a bit stream to be transmitted by the VCSEL and a compound semiconductor based detector to measure its output as well as an IR card to locate it. The detector output was fed to an oscilloscope to compare it with the transmitted signal.

4. EXPERIMENTAL RESULTS

The photovoltaic modules were tested both electrically and optically. The source meter was used to bias the diodes and measure the current. The response was then plotted for individual as well as series connected devices. The response was also measured using a semiconductor parameter analyzer and a probe station. A typical set of result for individual as well as series connected devices is provided here.

Diode	Open Circuit Voltage	Short Circuit Current
Deep N-Well	0.8V	50uA
Substrate	0.6V	250uA
Surface	0.7V	40uA
2 Diodes	1.1V	30uA
3 Diodes	1.5V	25uA

Table 1. Measurement data of CMOS photovoltaics of different configurations

A typical set of results for VCSEL is shown in figure 8. As can be seen in the I-V curves, the threshold voltage remained the same after the etching, and at the same driving voltage past the threshold, the current actually increased for the etched VCSEL chip, possibly due to less leakage into the substrate.
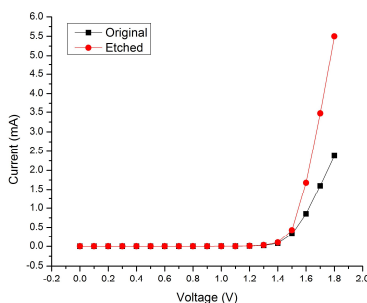

Fig. 8 I-V curves of a VCSEL chip before and after etching

5. CONCLUSION

In this work, we demonstrated use of all-optical links for both power transfer and communication for fully wireless implants. We showed that sufficiently high voltages and currents can be generated from miniaturized integrated photovoltaic devices if concentrated laser light is used to power these devices. We presented a topology which enables connecting three diodes in series in deep N-Well based CMOS processes to achieve high (1.5V) voltages. We also showed that high currents can be generated using substrate diodes due to large absorption region in these devices while still having small lateral footprint. Finally, we showed that optical communication can be done using ultra-small lasers bonded to the CMOS platform. This makes it possible to use completely optical methods for fully wireless implants and leads the way towards their miniaturization.

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