

## Bionic Vision: A Reality

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**Abstract:** Augmenting virtual world with reality promises to brighten the future of mankind. This paper aims to construct a novel contact lens capable of augmenting the reality with cyber world. A System of this kind should be competent enough to receive and analyze the images that a human being perceives and simultaneously boost the same vision by superimposing additional data. Such a system requires nano-scale fabrication and miniaturization of various components forming a complex circuitry and assembly of those circuitries on the contact lens using state of the art process. Similarly non-toxicity of the components, extraction of images that are perceived without hampering the vision, wireless transmission and reception of the power, development of a portable power source for the system are some of the other challenges faced along with the basic construction of the lens. The varied challenges are taken into consideration and addressed to develop a full-fledged working system.

### 1. Introduction

Bionic vision has fascinated mankind for a long time. Humans have often conjured up imaginations in numerous science fiction movies where characters like the Iron man sees the world with data superimposed on his visual field— virtual captions that enhance the suit's scan of a scene and in numerous fiction stories by authors like Vernor Vinge, characters rely on electronic contact lenses, rather than smart phones or brain implants, for seamless access to information that appears right before their eyes. A large body of research were carried out in past decades identified with this concept and in the process arrived upon various inventions like the virtual glasses, smart goggles etc. But nothing has proved to be of greater interest when compared to the electronic contact lens as they are a lot secretive, less cumbersome, less bulky and undetectable to a third person. Given this context, this paper tries to identify methods which would enable realizing a smart contact lens and implementation the bionic vision.

Over the last few decades, conventional contact lenses have been used to correct vision. Advances in manufacturing have changed the material used for contact lens manufacturing, from glass, polymers used in gas-permeable contacts, to current material made up of highly engineered hydro gels. Recent advances in nano and micro fabrication have enabled the construction of exceedingly small electronic, photonic, and sensing devices which promise to transition contact lenses to the next level of sophistication by turning them into functional Microsystems. In particular, the promise of integrating display or sensing components onto a contact lens will offer a venue for construction of novel devices. The hurdles that stand in the way of implementing such a lens include implementing nano-scale circuitry on the lens to display illuminated pixels, providing the circuitry on lens

with wireless power, reception of images from the lens for digital processing. Another issue is the inclusion of extra peripherals outside the lens like a novel power source which is portable, eco friendly and has a long life and a personal computer to synchronize and analyze all data that are sent from the smart lens. When discussions come up with regards to generating images on the lens close to the eye one needs to take care of a few major hurdles that hinder the implementation. The fact that images produced very close to the eyes (less than 25 cm from the eye) cannot be perceived by it needs to be taken into account while designing the system. All subcomponents of the system need show biocompatibility along with the needs for circuitry to enable non hindrance of normal visions is a vital aspect to be addressed. The system proposed will include an array of different components like silicon transistors and diode , bifocal and Fresnel micro lenses, nontoxic micro led , power harvesting ICS, RF systems (antennas and modules) for wireless data and power transmission . Step wise analysis and working of each system and their synchronization with each other will enable perfect bionic sight.

### 2. Prerequisites

Certain prerequisites are required for the detailed explanation of position of circuitry and focusing of light rays on the retina as well as the digital screen.

#### A. Blind spot

A small point on the retina of human eye where the optic nerve meets is called a blind spot. Since there are no photoreceptors (rods and cones) in this particular area, it cannot respond to any light

stimulation. Every eye has a blind spot and these are aligned symmetrically so that most of the time, one eye's field of vision will compensate for the loss of vision in the other. The figure 1 illustrates the following point

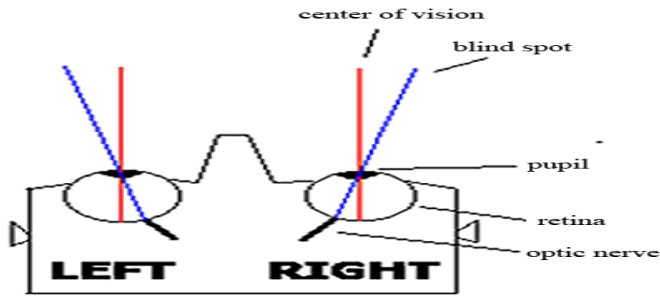


Figure 1

The projection of this spot on the surface of the eye will be predominantly used for placing the monolithic circuits. This aperture is a few millimeters in width and is more than enough to accommodate the entire circuitry.

### B. Micro lenses

A micro lens is a small lens, generally with a diameter as small as 10 micrometers. Micro lenses are highly advantageous as they can be fabricated on plastic substrate. Also the focal lengths, diffraction and reflection properties of these lenses can be easily manipulated according to the users' specification.

Fresnel micro lenses and Bifocal micro lenses are the two classes of micro lenses that are to be used in this system.

#### i. Fresnel micro lenses

Micro Fresnel lens is a class of micro lenses with superior focusing properties which can be easily fabricated on substrates. These lenses can be designed to have ultra short focal length. The Fresnel lens reduces the amount of material required compared to a conventional spherical lens by dividing the lens into a set of concentric annular sections known as Fresnel zones. These zones are responsible for attaining such short focal lengths. The human eye, even with its minimum focal distance of several centimeters, cannot resolve objects on a contact lens. These lenses come in handy to tackle such problem.

#### ii. Bifocal micro lenses

The bifocal micro lenses are novel optical components, which have the capability of producing two focal points along optical axis. Since it belongs to the micro lens category, it has a small diameter which can be used for fabrication on plastic substrates which have very short focal lengths. These lenses will be used primarily to focus lights incident on the contact lens on both the retina as well as the digital screen.

### 3. On Lens Circuitry

The contact lens display comprises of a light emitting diode, an antenna, an integrated circuit (IC) for power harvesting and LED control and a polymer substrate with electrical interconnects. An external transmitting antenna emits RF radiation that is collected by the on-lens antenna. The integrated circuit rectifies and stores this energy, and duty cycles power to the LED at a frequency sufficiently high to give the appearance of continual light emission. The current circuitry describes the circuit for a single pixel system.

#### A. Method of Fabrication

To realize the circuits on the contact lens surface the process called self assembly is adopted. Self assembly process is practiced widely in those areas where the fabrication has to be in micro-scale and the substrate is delicate and can get easily deformed. The circuit may involve the use of various micrometer scale functional devices like silicon based field effect transistors, photodiodes etc. The fabrication involves assembling silicon micro components on a silicon wafer and then releasing them to yield a collection of freestanding micro components resembling fine powder. Each of the micro components carries metal contacts and has a specifically defined shape. Separately, the plastic templates are prepared with embedded metal interconnects and binding sites with various shapes made of polymer. At the bottom of the binding sites, it is arranged to have the areas occupied by an alloy with a low melting point. The self-assembly process involves submerging both the silicon micro components and the plastic template into a fluid and agitating to induce movement of the micro components over the substrate. When the shape of a micro component and the corresponding components are well matched, the micro component falls into the well allowing contact between the molten alloy at the bottom of the well and the metal pads positioned on the surface of the micro component. The resultant capillary force keeps the micro component in the well, preventing the fluid flow to dislodge the bound part. If the component enters the well upside-down, a capillary connection will not be made and fluid force forces the component out of the well. After

the completion of the self-assembly process, the temperature is lowered to solidify the molten alloy and to make the mechanical and electrical connections between the micro components and the template permanent. [i]

Figures listed below explains the process of self assembly in a two step process

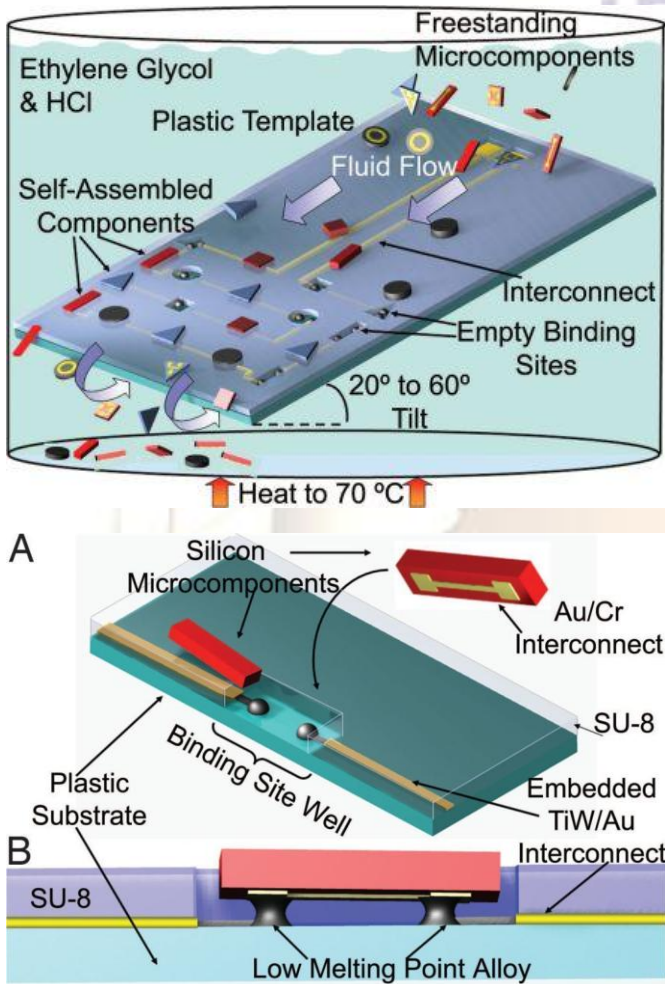


Figure 2

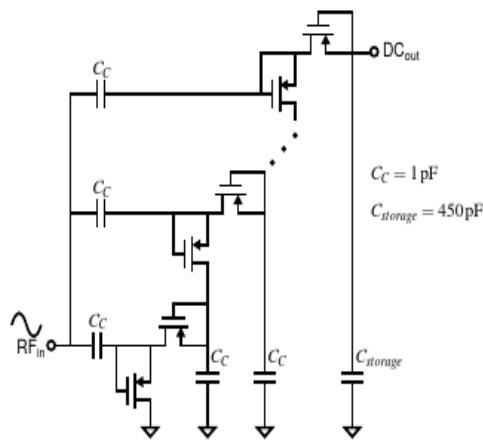
**B. Components (Image generation and power Transmission)**

**POWER HARVESTING IC**

Minimum input power to the antenna and maximum allowed transmit power in 2.4 GHz band results in choosing of ISM band for the wireless link. Two constraints on this minimum

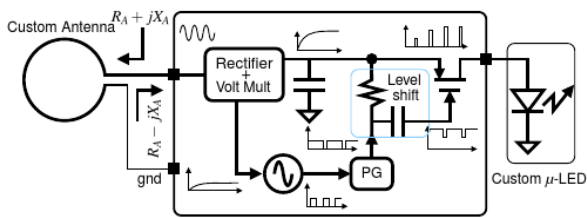
input power are the antenna/rectifier power efficiency and the input voltage amplitude to the rectifier which in turn is constrained by the LED turn-on voltage, rectifier threshold and impedance matching to the antenna. Figure shows the architecture of the CMOS prototype chip containing the power harvesting, storage capacitor and power management circuitry. It houses 450 pF of integrated storage capacitance. Some of the important challenges in making an integrated RF power harvesting system are designing an efficient rectifier, an intelligent, robust power management system, and realizing a high-density on-chip storage capacitor. To avoid junction and oxide breakdown of the transistors (0.13 μm CMOS) rectifier scheme shown in Fig. 6 is chose. CMOS process that provides low threshold transistors for enhanced rectifier sensitivity is selected. The diodes are realized using PMOS transistors with the body terminal tied to the source in order to eliminate the body effect.

The optimal number of stages in the multiplying rectifier was determined by considering the trade-off between its power efficiency, output voltage, input impedance for matching and the micro-LED load (capacitor charging time). Eight stages which provides approximately  $8 \cdot (V_{RF} - V_t) \approx 3.6V$  of DC output for 750mV RF input and 300mV threshold Voltage are used for rectifier circuitry. For maximum energy storage on the capacitor, the DC voltage must be maximized under the breakdown voltage constraint (10 V). However, the large number of stages required for achieving this high voltage leads to increased capacitor charging time, degraded quality factor of the input impedance and unreasonable values for the antenna impedance matching. Another important aspect of the rectifier design is the choice of coupling capacitor (Cc). It should be much larger than the parasitic capacitance of the MOS diodes but should be small enough to facilitate input matching and higher quality factor of the input impedance of the chip (for passive voltage gain). 1 pF was found to be a good compromise. For the application of on-lens display system using custom LEDs, the optimal number of stages was found to be eight.



Eight-stage rectifier design using low- $V_t$  PMOS devices.

Figure 3



Architecture of the custom chip.

Figure 4

A robust power management circuit is absolutely crucial for ensuring reliable circuit functionality in the face of scarce power resources on chip. The power management circuit allows powering the LED for approximately 3% of the time by modulating the 3.3V PMOS switch. The on-chip ring oscillator shown in figure derives its power supply ( $\sim 1V$ ) from the second stage of the cascaded rectifier. Each inverter in the 3-stage oscillator uses stacked high- $V_t$  devices for low leakage and low-power of operation ( $\sim 500nW$  at 1 MHz). The frequency doubling pulse generation circuit generates an active low pulse at each transition of the oscillator output of approximately  $0.015/f$  long duration where  $f$  is the frequency of the ring oscillator. This means that the pulse generator effectively generates active low pulses of 3% duty cycle at a frequency  $2f$ . The level shifter circuit uses the output of rectifier to up-convert the active-low pulses with active high

and active low being 3.5 and 2.5V respectively. The difficulty in realizing very small high quality tank circuits on the plastic substrate and the extremely small size of the chip prevents any passive impedance matching tank circuit for passive voltage gain. This results in loss of sensitivity of the rectifier. [0]

## ANTENNA

### 1. Design

The primary challenge for antenna design in small systems is to achieve adequate efficiency. Antenna efficiency is strongly influenced by antenna size, and efficiency drops precipitously if the antenna is much smaller than the electromagnetic wavelength. One potential solution to improve the antenna performance with reduced size is to design the system to operate at high frequency. Therefore 2.4 GHz ISM frequency band was chosen. A loop antenna was determined to be a practical choice to avoid impeding vision. [0]

### 2. Implementation

Antenna design was constrained by contact lens size and eye physiology, and therefore a 5.0 mm radius loop antenna was used to harvest RF energy but leave the pupil unobstructed. Two factors determine the frequency of operation: (1) power received by the on-lens loop antenna, and (2) antenna-to-chip impedance matching. The tests were conducted maintaining a distance of 1 meter between the source and lens and 1 watt power was transmitted. In free space, modeled received power peaked at  $\sim 117 \mu W$  at approximately 2.0 GHz. At lower frequencies, received power is limited by on-lens antenna efficiency, while path loss dominates at higher frequencies.

Also the antenna testing was simulated in saline water for more realistic test and the power consumption, was shorter on the eye (saline surrounding) than in free space. However, as contact lens and transmitting antenna separation decreases, near field interactions begins to dominate and more power is available. [0]

### 3. Micro LEDs

In the initial stages of development red LEDs were used to generate a pixel, but due to the toxicity of aluminum arsenide, blue LEDs were preferred. Blue micro LEDs are grown on gallium arsenide which is harmless to the human eye meeting biological standards. GaN and its alloys were deemed suitable due to non-toxicity, high efficiency and appropriate achievable emission wavelength. The micro-LED design, with peak intensity at  $\sim 475$  nm, is adequate to illuminate the retina. [0]

#### 4. Fresnel Fabrication

Since the images generated on the contact lenses cannot comply with the minimum focal distance of 25 cm away from the eye, they had to be focused alternatively on retina. Hence the images generated had to be passed through subsidiary lens. The LEDs fabricated were thus made of Fresnel lenses. As discussed earlier, Fresnel lenses can have very short focal length and thus helps in focusing the pixels on LEDs in such a way that they appear 1 meter floating when seen by the wearer.

#### 5. Summary

The whole system is encapsulated in a transparent polymer creating a system to generate images perceivable by the wearer and not harming his eyes.

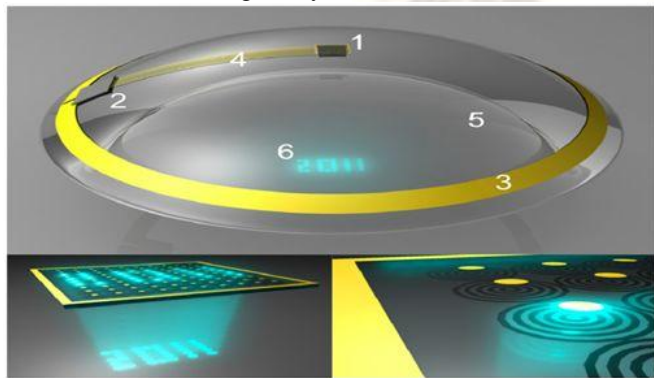


Figure 5

Figure 5 (TOP) illustrates each of the subcomponents. (The numbering of subcomponents coincides with the numbering of the detailed description.)

Figure 5 (Bottom) The image to the left shows a 100 micro LEDs array displaying numeric value, (Right) number of leds with Fresnel lens mounted on them

#### C. Components (Image processing )

One needs to understand the formation of images on eye in order to simulate them and process them.

When light falls on the surface of one's eye, it is converged and focused to the back of the eye to a part called as retina. Retina serves as a screen for image formation and passes on the information through optic nerve to the brain.

The Formation of the Retinal Image

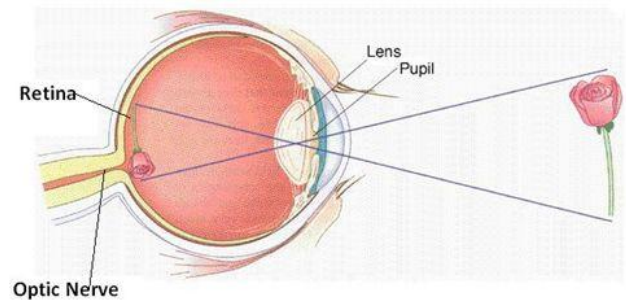


Figure 6

In order simulate human vision digitally, the rays of light need to fall on some kind of digital screen and at the same time on the retina as well. The digital screen that is proposed is a pixel sensor with Bayer's layer which is hardly a few micrometers in size and can be easily accommodated in the center of contact lenses above the blind spot where the other circuits are placed. Since monolithic integration of circuits is practiced, pixel sensor will be at the top most layers followed by all other circuitries. The same self assembly technique is adopted for the fabrication of sensor.

If the pixel sensor is integrated, then the light of the image falling on the retina now need to converge on two points instead of one. As discussed earlier, bifocal micro lens is apt for such a situation where the only criteria being that both the screens should be on the same optical axis. Since the pixel sensor is mounted on the center of the eye, it is exactly ahead of the retina thus solving the problem. Bifocal micro lens are fabricated on the same gallium arsenide alloys as the LEDs were manufactured. The focal lengths are so adjusted that the first focal length is fairly shorter focused on the sensor while the other focal point is inside the eye on the retina. On an average a contact lens is 7 millimeter in radius whereas a bifocal micro lens is around 5 micro meters in radius. If roughly calculated, more than a million micro lenses can be fabricated on the surface of the contact lenses.

Now that the logic of image perception is solved, the final step is the data transceiver that needs to be implemented beneath the pixel sensor for communication with a computer. The detailed explanation of the pixel sensor and transceiver circuit follows.

**i. Pixel Sensor**

A basic pixel sensor comprises of the following:

**CMOS Image Sensors**

These sensors help reading various intensities of photons and stores them. They are preferred over conventional ccds because CMOS image sensors integrate the pixel along with circuitry, unlike CCDs, which requires processing circuits on a separate chip. Unlike the earlier the current CMOS sensors have relatively low noise and have quality equal to CCD's.

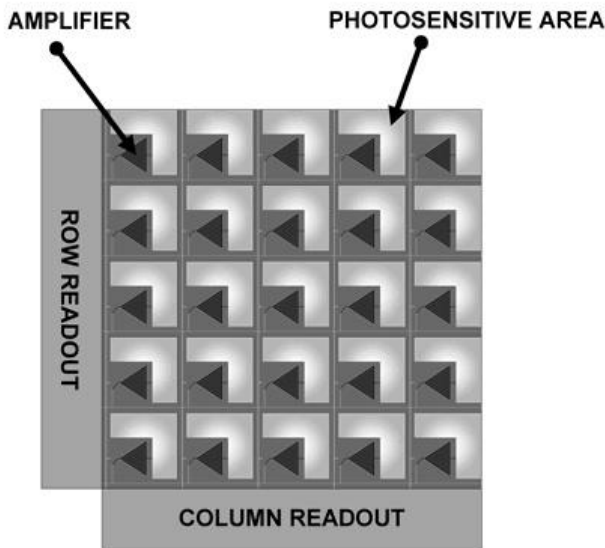


Figure 7

There are two basic kinds of CMOS image sensors—passive and active.

**Passive Pixel Sensor**

Passive-pixel sensors (PPS) were the first image-sensor devices used in the 1960s. In passive-pixel CMOS sensors, a photo-sensor converts photons into an electrical charge. This charge is then boosted on chip by an amplifier. Since the charge is carried through several stages, there is a significant amount of noise added to the photo-signal in this process. To cancel out this noise, additional processing steps are required, sometimes on chip and sometimes off chip.

**Active Pixel Sensor**

Active-pixel sensors (APSs) reduce the noise associated with passive-pixel sensors. Each pixel has an extra circuit, an amplifier, which helps cancels the noise associated with the pixel. It is from this concept that the active-pixel sensor gets

its name. The performance of this technology is high and also allows for a larger image array and higher resolution. Hence this sensor is used in the lens circuitry for image reception.

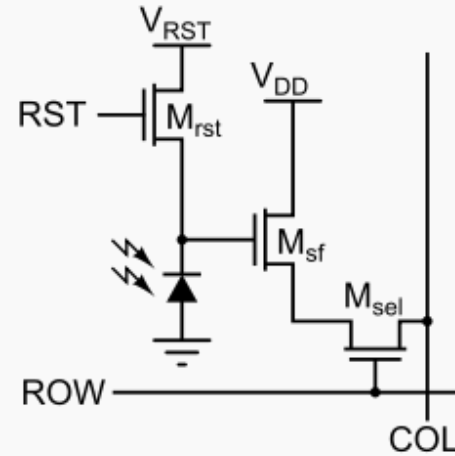


Figure 8: A three-transistor active pixel sensor

The standard CMOS APS pixel today consists of a photo-detector (a pinned photodiode), a floating diffusion, a transfer gate, reset gate, selection gate and source-follower readout transistor—the so-called 4T cell. The pinned photodiode was originally used in interline transfer CCDs due to its low dark current and good blue response, and when coupled with the transfer gate, allows complete charge transfer from the pinned photo diode to the floating diffusion (which is further eliminating lag. The use of intra pixel charge transfer can offer lower noise by enabling the use of correlated double sampling (CDS). The Noble 3T pixel is still often used since the fabrication requirements are easier. The 3T pixel comprises the same elements as the 4T pixel except the transfer gate and the pinned photo diode. The reset transistor,  $M_{rst}$ , acts as a switch to reset the floating diffusion which acts in this case as the photo diode. When the reset transistor is turned on, the photodiode is effectively connected to the power supply,  $V_{RST}$ , clearing all integrated charge. Since the reset transistor is n-type, the pixel operates in soft reset. The read-out transistor,  $M_{sf}$ , acts as a buffer (specifically, a source follower), an amplifier which allows the pixel voltage to be observed without removing the accumulated charge. Its power supply,  $V_{DD}$ , is typically tied to the power supply of the reset transistor. The select transistor,  $M_{sel}$ , allows a single row of the pixel array to be read by the read-out electronics. Other innovations of the pixels such as 5T

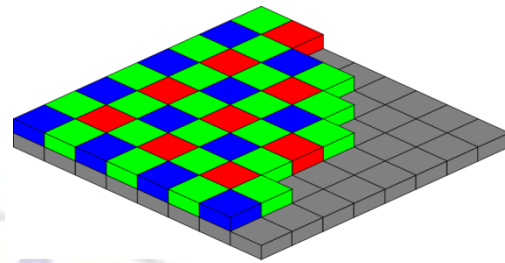
and 6T pixels also exist. By adding extra transistors, functions such as global shutter, as opposed to the more common rolling shutter, are possible. In order to increase the pixel densities, shared-row, four-ways and eight-ways shared read out, and other architectures can be employed. A variant of the 3T active pixel is the Foveon X3 sensor invented by Dick Merrill. In this device, three photodiodes are stacked on top of each other using planar fabrication techniques, each photodiode having its own 3T circuit. Each successive layer acts as a filter for the layer below it shifting the spectrum of absorbed light in successive layers. By deconvolving the response of each layered detector, red, green, and blue signals can be reconstructed.[vii]

**ii. BAYERS' FILTER**

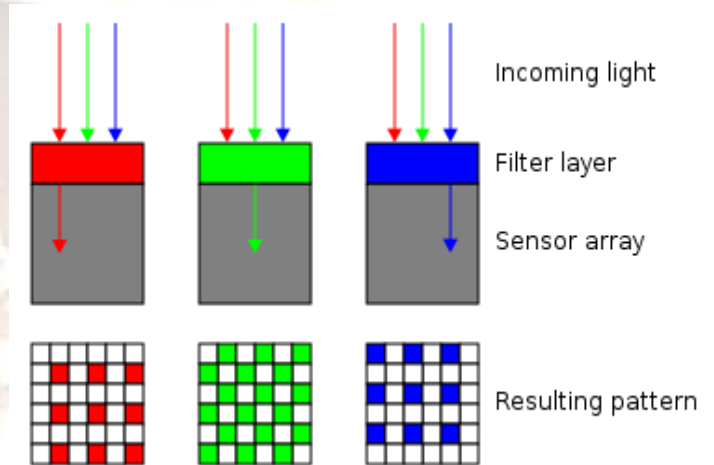
The images obtained from this sensor only record intensity and are colorless. To attribute the specific colors that one's vision perceives BAYERS' filter is used. A Bayers' filter mosaic is a color filter array (CFA) for arranging RGB color filters on a square grid of photo sensors. Its particular arrangement of color filters is used in most single-chip digital image sensors used in digital cameras, camcorders, and scanners to create a color image. The filter pattern is 50% green, 25% red and 25% blue, hence is also called RGBG, GRGB, or RGGB. It is named after its inventor, Bryce E. Bayers' of Eastman Kodak.

Bryce Bayers's patent (in 1976) called the green photo sensors luminance-sensitive elements and the red and blue ones chrominance-sensitive elements. Twice as many green elements as red or blue are used to construct the filter layer to mimic the physiology of the human eye. The luminance perception of the human retina uses M and L cone cells combined, during daylight vision, which are most sensitive to green light. These elements are referred to as sensor elements, sensels, pixel sensors, or simply pixels; sample values sensed by them, after interpolation, become image pixels.

The raw output of Bayers'-filter cameras is referred to as a Bayers' pattern image. Since each pixel is filtered to record only one of three colors (figure 8), the data from each pixel cannot fully determine color on its own. To obtain a full-color image, various de-mosaicing algorithms can be used to interpolate a set of complete red, green, and blue values for each point. Different algorithms requiring various amounts of computing power result in varying-quality final images. This can be done using the raw data directly from the sensor.

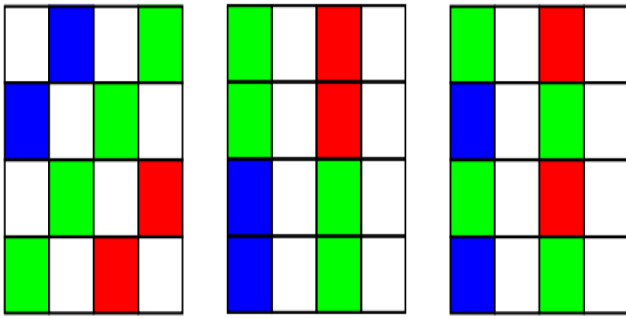


**Figure 9: The Bayers' arrangement of color filters on the pixel array of an image sensor**



**Figure 10: Profile/cross-section of sensor**

On June 14, 2007, Eastman Kodak announced an alternative to the Bayers' filter: a color-filter pattern that increases the sensitivity to light of the image sensor in a digital camera by using some "panchromatic" cells that are sensitive to all wavelengths of visible light and collect a larger amount of light striking the sensor. They present several patterns, but none with a repeating unit as small as the Bayers' pattern's 2x2 unit.



**Figure 11: Three new Kodak RGBW filter patterns**

It is a standard process to mount the Bayer's" layer on the active pixel sensor to emulate the human vision as it is.

This layer mounted on sensor together serves the purpose of forming the image and serving as the digital eye for our system.[vi]

### iii. Data Transceiver

Various video and image transceiver circuits are commercially available which are employed in cctvs and spy cameras. While the circuit can be reused as it is, miniaturization and fitting them into the same chip inside the lens with other circuits need to be analyzed. As explained earlier these circuits can use the same antenna that is used for power transmission to send constant stream of images one perceives and can receive virtual information of what one sees from the processor.

## 4. External peripherals

### A. Power supply

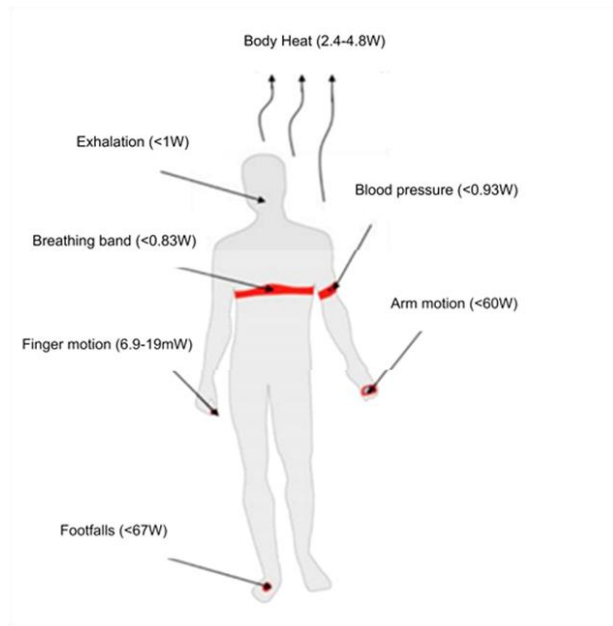
Implantable or wearable devices will only significantly increase quality of life if they are unobtrusive to the users in terms of use and maintenance. It is especially important to eliminate maintenance for implantable devices, for which replacement of the power source in particular must be avoided. While some implanted sensors can be totally passive and used in conjunction with active equipment when a measurement is needed, and some active devices could be powered up occasionally by wireless energy transfer, many require a continuous source of electrical power. Ideally, all implantable medical devices would have a power-supply

lifetime as long as the required operational lifetime, thus keeping surgery, and cost, to a minimum. Bionic lenses if not a lifesaving implant, are for sure a life enhancing device. Since generation of energy from batteries is either non portable or insufficient one is forced to look into other options. Energy can be harvested indirectly from everyday human actions or by intentionally generated actions. Indeed, products that operate in this mode, e.g. torches, radios, watches, have been on the market for years. At the same time, there has been a significant body of research on human generated power which can find potential applications particularly in low power biomedical applications. The related systems need to be wearable and typically consist of sensors, signal conditioning electronics and wireless transmission technology. More power allows longer operation, higher sampling rates and wireless transmission over a longer distance, and support of additional features. Therefore powerful, low weight and compact energy storage devices and energy harvesting from the human body are crucial technologies for extended and reliable operation.

### B. Potential human power sources

Power may be recovered passively from body heat, breathing, blood pressure, arm motion, typing, and walking or actively through user actions such as winding or pedaling. In cases where the devices are not actively driven, only limited power can generally be harvested without inconveniencing or annoying the user. A summary of the potential power sources and the total power from various body-centered actions is provided in the figure





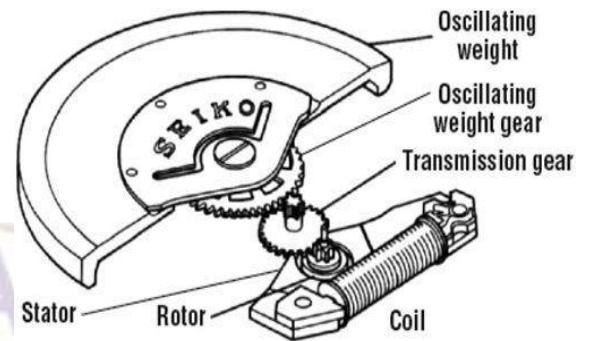
**Figure 12 : Viable power that can be extracted from human body**

One can see that the power output from daily activities is more than what is needed for our system. Even after considering the power loss, one should be well placed to power his own system sufficiently, if he is in a position to harness these energies. Let us look into some of the technologies existing in market.

a. Kinetic watch (harnessing kinetic energy of arm motion )

This technology is currently in use only to power the battery of the watch but can be extended to power other application as well. Seiko ltd holds the patent of this technology. The principle is as follows:-

A rotating pendulum inside the case is attached to a relatively large gear which meshes with a very small pinion. As the wearer moves, the pendulum turns and spins the pinion at a very high speed - up to 100,000rpm. This is coupled to a miniature electrical generator which charges a storage device which is a capacitor(s) or a rechargeable battery. A typical full charge will last between two weeks and six months [0]

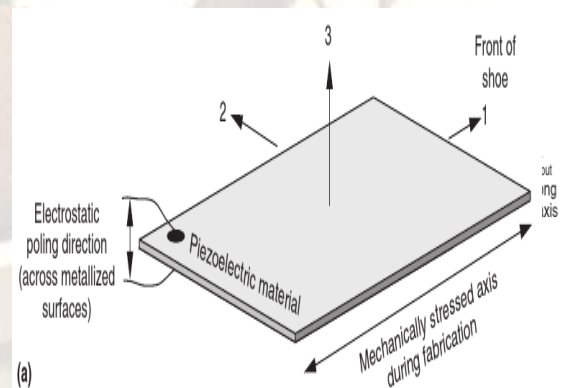


**Figure 13: The Working model of kinetic watch**

b. Shoe Mounted Piezoelectric (converting footfalls)

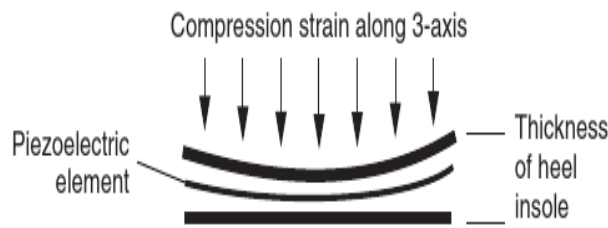
The piezoelectric effect—a material’s capacity to convert mechanical energy into electrical energy, and the inverse—is observable in a wide array of crystalline substances that have asymmetric unit cells. When an external force mechanically strains a piezoelectric element, these polarized unit cells shift and align in a regular pattern in the crystal lattice. The discrete dipole effects accumulate, developing an electrostatic potential between opposing faces of the element. Relationships between the force applied and the subsequent response of a piezoelectric element depend on three factors the structure’s dimensions and geometry, the material’s piezoelectric properties, and the mechanical or electrical excitation. [0]

Figure 14(a) depicts the piezoelectric effect on a suitable material, while Figure 14(b) depicts the construction on insole piezoelectric material.



**Figure 14 (a)**

Figure 14 (b) Working insole models



The piezoelectric element is fitted into the sole of the shoe taking into account the wearers comfort and the voltages induced by different stress are harnessed and stored in the circuitry just ahead of the sole. It is illustrated in figure 14

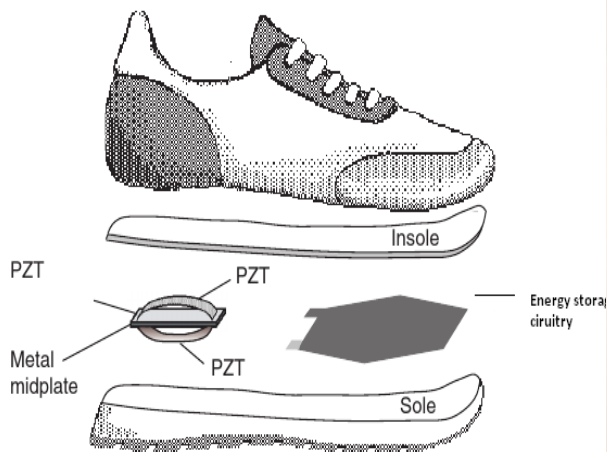


Figure 15 : Overall System of Piezoelectric shoe

Many other technologies like the harness of heat from one's body, the compression and expansion of chest's movement are under the research process for extraction of energy. The above discussed options are most contemporary and feasible in our system. If these bio energies are implemented, the worry about generation of power and its losses can be put on the back burner. While this is only the beginning, the possibilities of such technologies are endless.

### C. Data Processor

The obvious choice for data processing would be a computer. A dongle for wireless transmission and reception of data at the required frequency for constant stream of images are commercially available. A dedicated application and

interfacing the computer with the transceiver circuit needs to be implemented

### 4. Inference

There has been stupendous research and testing on the system proposed so far. Contact lens with a very minimal and essential sub system were fabricated and tested on a rabbit. The lens was mounted on the rabbit eye and tested for more than 20 minutes with successful working of each subsystem built inside the lens. After the test, the subject's eyes were tested for anomaly due to the test and to the lens's credit none were found. Several points which are to be worked upon were noted. Concerns about the amount of oxygen permeability, range of power transmission etc... still prevail which need to be addressed before the prototype comes into production. In the near future, bionic vision will surely evolve to be a reality and not a science fiction anymore.

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