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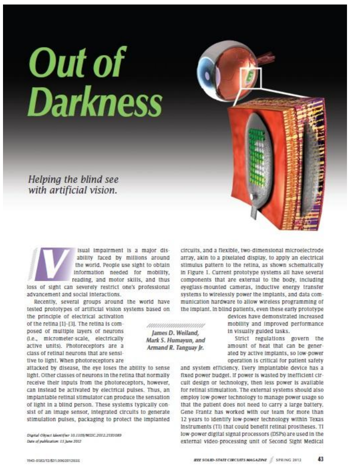

Out of Darkness

Helping the blind see with artificial vision.

James D. Weiland, Mark S. Humayun, and Armand R. Tanguay Jr.

Visual impairment is a major disability faced by millions around the world. People use sight to obtain information needed for mobility, reading, and motor skills, and thus loss of sight can severely restrict one's professional advancement and social interactions.

Recently, several groups around the world have tested prototypes of artificial vision systems based on the principle of electrical activation of the retina [1]–[3]. The retina is composed of multiple layers of neurons (i.e., micrometer-scale, electrically active units). Photoreceptors are a class of retinal neurons that are sensitive to light. When photoreceptors are attacked by disease, the eye loses the ability to sense light. Other classes of neurons in the retina that normally receive their inputs from the photoreceptors, however, can instead be activated by electrical pulses. Thus, an implantable retinal stimulator can produce the sensation of light in a blind person. These systems typically consist of an image sensor, integrated circuits to generate stimulation pulses, packaging to protect the implanted circuits, and a flexible, two-dimensional microelectrode array, akin to a pixelated display, to apply an electrical stimulus pattern to the retina, as shown schematically in Figure 1. Current prototype systems all have several components that are external to the body, including eyeglass-mounted cameras, inductive energy transfer systems to wirelessly power the implants, and data communication hardware to allow wireless programming of the implant. In blind patients, even these early prototype devices have demonstrated increased mobility and improved performance in visually guided tasks.

Strict regulations govern the amount of heat that can be generated by active implants, so low-power operation is critical for patient safety and system efficiency. Every implantable device has a fixed power budget. If power is wasted by inefficient circuit design or technology, then less power is available for retinal stimulation. The external systems should also employ low-power technology to manage power usage so that the patient does not need to carry a large battery. Gene Frantz has worked with our team for more than 12 years to identify low-power technology within Texas Instruments (TI) that could benefit retinal prostheses. TI low-power digital signal processors (DSPs) are used in the external video-processing unit of Second Sight Medical

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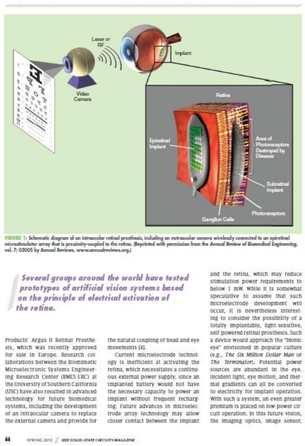

FIGURE 1: Schematic diagram of an intraocular retinal prosthesis, including an extraocular camera wirelessly connected to an epiretinal microstimulator array that is proximity-coupled to the retina. (Reprinted with permission from the *Annual Review of Biomedical Engineering*, vol. 7; ©2005 by Annual Reviews, www.annualreviews.org.)

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Products' Argus II Retinal Prosthesis, which was recently approved for sale in Europe. Research collaborations between the Biomimetic Microelectronic Systems Engineering Research Center (BMES-ERC) at the University of Southern California (USC) have also resulted in advanced technology for future biomedical systems, including the development of an intraocular camera to replace the external camera and provide for the natural coupling of head and eye movements [4].

Current microelectrode technology is inefficient at activating the retina, which necessitates a continuous external power supply, since an implanted battery would not have the necessary capacity to power an implant without frequent recharging. Future advances in microelectrode array technology may allow closer contact between the implant and the retina, which may reduce stimulation power requirements to below 1 mW. While it is somewhat speculative to assume that such microelectrode development will occur, it is nevertheless interesting to consider the possibility of a totally implantable, light-sensitive, self-powered retinal prosthesis. Such a device would approach the "bionic eye" envisioned in popular culture (e.g., *The Six Million Dollar Man* or *The Terminator*). Potential power sources are abundant in the eye. Incident light, eye motion, and thermal gradients can all be converted to electricity for implant operation. With such a system, an even greater premium is placed on low-power circuit operation. In this future vision, the imaging optics, image sensor,

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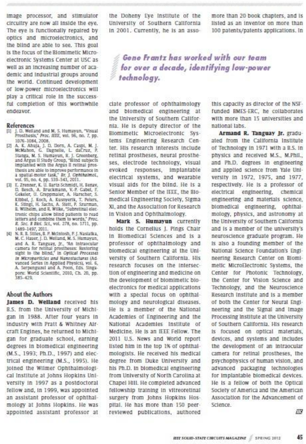

image processor, and stimulator circuitry are now all inside the eye. The eye is functionally repaired by optics and microelectronics, and the blind are able to see. This goal is the focus of the Biomimetic Microelectronic Systems Center at USC as well as an increasing number of academic and industrial groups around the world. Continued development of low-power microelectronics will play a critical role in the successful completion of this worthwhile endeavor.

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About the Authors

James D. Weiland received his B.S. from the University of Michigan in 1988. After four years in industry with Pratt & Whitney Aircraft Engines, he returned to Michigan for graduate school, earning degrees in biomedical engineering (M.S., 1993; Ph.D., 1997) and electrical engineering (M.S., 1995). He joined the Wilmer Ophthalmological Institute at Johns Hopkins University in 1997 as a postdoctoral fellow and, in 1999, was appointed an assistant professor of ophthalmology at Johns Hopkins. He was appointed assistant professor at the Doheny Eye Institute of the University of Southern California in 2001. Currently, he is an associate professor of ophthalmology and biomedical engineering at the University of Southern California. He is deputy director of the Biomimetic Microelectronic Systems Engineering Research Center. His research interests include retinal prostheses, neural prostheses, electrode technology, visual evoked responses, implantable electrical systems, and wearable visual aids for the blind. He is a Senior Member of the IEEE, the Biomedical Engineering Society, Sigma Xi, and the Association for Research in Vision and Ophthalmology.

Gene Frantz has worked with our team for over a decade, identifying low-power technology.

Mark S. Humayun currently holds the Cornelius J. Pings Chair in Biomedical Sciences and is a professor of ophthalmology and biomedical engineering at the University of Southern California. His research focuses on the intersection of engineering and medicine on the development of biomimetic bioelectronics for medical applications with a special focus on ophthalmology and neurological diseases. He is a member of the National Academies of Engineering and the National Academies Institute of Medicine. He is an IEEE Fellow. The 2011 U.S. News and World report listed him in the top 1% of ophthalmologists. He received his medical degree from Duke University and his Ph.D. in biomedical engineering from University of North Carolina at Chapel Hill. He completed advanced fellowship training in vitreoretinal surgery from Johns Hopkins Hospital. He has more than 150 peer-reviewed publications, authored more than 20 book chapters, and is listed as an inventor on more than 100 patents/patents applications. In this capacity as director of the NSF-funded BMES-ERC, he collaborates with more than 15 universities and national labs.

Armand R. Tanguay Jr. graduated from the California Institute of Technology in 1971 with a B.S. in physics and received M.S., M.Phil., and Ph.D. degrees in engineering and applied science from Yale University in 1972, 1975, and 1977, respectively. He is a professor of electrical engineering, chemical engineering and materials science, biomedical engineering, ophthalmology, physics, and astronomy at the University of Southern California and is a member of the university's neuroscience graduate program. He is also a founding member of the National Science Foundation's Engineering Research Center on Biomimetic MicroElectronic Systems, the Center for Photonic Technology, the Center for Vision Science and Technology, and the Neuroscience Research Institute and is a member of both the Center for Neural Engineering and the Signal and Image Processing Institute at the University of Southern California. His research is focused on optical materials, devices, and systems and includes the development of an intraocular camera for retinal prostheses, the psychophysics of human vision, and advanced packaging technologies for implantable biomedical devices. He is a fellow of both the Optical Society of America and the American Association for the Advancement of Science.

IEEE SOLID-STATE CIRCUITS MAGAZINE SPRING 2012 45