High-density cochlear implants with position sensing and control

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A B S T R A C T
Silicon-based thin-film technology has been used to develop high-density cochlear electrode arrays with up to 32 sites and four parallel channels of simultaneous stimulation. The lithographically-defined arrays utilize a silicon-dielectric-metall-parylene structure with 180μm-diameter IO sites on 250 μm centers. Eight on-board strain gauges allow real-time imaging of array shape during insertion, and a tip sensor measures forces on any structures contacted in the scala tympani (e.g., the basilar membrane). The array can be pre-stressed to hug the modiolus, which provides position reference. Tip position can be resolved to better than 50 μm. Circuitry mounted on the base of the array generates stimulating currents, records intra-cochlear responses and position information, and interfaces with a custom microcontroller and inductively-coupled wireless interface over an eight-lead ribbon cable. The circuitry delivers biphasic 500 μA current pulses with 4 μA resolution and a minimum pulse width of 4 μs. Multiple sites can be driven in parallel to provide higher current levels. Backing structures and articulated insertion tools are being developed for dynamic closed-loop insertion control.

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1. Introduction
Since their introduction in the 1980s, cochlear implants have become highly successful neural prostheses, with over 120,000 profoundly deaf and severely hearing impaired users worldwide (Cochlear Implants, 2005). By directing current through 16–22 intra-cochlear wire electrodes, a cochlear implant exploits the frequency-to-place mapping in the cochlea of the inner ear to directly stimulate the auditory nerve electrically, bypassing the defective hair cells that in a normal individual would transduce sound energy into neural signals.

Although such devices have been remarkably effective, there remain significant variations in speech perception among patients exhibiting similar pre-implant etiologies, as well as difficulties in understanding tonal languages and appreciating music (Gfeller and Lansing, 1992; Gfeller et al., 2007; Xu et al., 2005), and understanding speech in a crowded room (Xu and Pfingst, 2008). A possible solution to these problems is to develop electrode arrays having significantly increased numbers of stimulating sites so that the arrays can more easily adapt to differing patterns of neural survival and make use of multi-polar current shaping to activate distinct nerve populations and enhance pitch perception (Rodenhiser and Spelman, 1995; Bonham and Litvak, 2008; Bhatti et al., 2003; Xu et al., 2008). However, scaling up the present hand-assembled wire-bundle-based electrode arrays is precluded by the size of the scala tympani, which tapers from a diameter of about 1 mm to about 200 μm over its length. This paper explores the use of lithographically-defined thin-film arrays capable of supporting site densities at least three times those of present systems. Similar technology has become widely used for penetrating electrode arrays for use higher in the auditory system (e.g., in the cochlear nucleus or auditory cortex) (Anderson, 2008; Lim et al., 2008; McCreery, 2008), providing high-density recording/stimulating sites as well as fluidic components for drug delivery and chemical sensing (Wise et al., 2004; Papageorgiou et al., 2006; Li et al., 2005). For cochlear use, the technology also enables the integration of position sensors on the array to help optimize in vivo placement, minimize insertion damage, and preserve any residual hearing (Wang et al., 2005). Position sensing is a first step toward a closed-loop dynamic position control system and is being developed in conjunction with pneumatically-controlled insertion devices. Circuitry for stimulus generation, recording, position sensing, and impedance testing can be incorporated at the base of the array. One of the vehicles for exploring this technology has been a 32-site 4-channel electrode array designed for animal (guinea pig) studies. The site densities and other features are consistent...