A Wireless, Mechanically Flexible, 25µm-Thick, 65,536-Channel Subdural Surface Recording and Stimulating Microelectrode Array with Integrated Antennas

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Abstract

This paper presents a fully wireless microelectrode array (MEA) system-on-chip (SoC) with 65,536 electrodes for non-penetrative cortical recording and stimulation, featuring a total sensing area of 6.8mm×7.4mm with a 26.5µm×29µm electrode pitch. Sensing, data telemetry, and powering are monolithically integrated on a single chip, which is made mechanically flexible to conform to the surface of the brain by substrate removal to a total thickness of 25µm allowing it to be contained entirely in the subdural space under the skull.

Keywords: CMOS, Implantable, MEA, UWB, WPT

System Architecture

We develop a brain-machine interface (BMI) device in which the implant is a single integrated circuit chip, positioned subdurally on the pial surface of the brain as shown in Fig. 1. The chip interfaces wirelessly to a "relay station" immediately outside the body over the implant, which contains both an ultra-wideband (UWB) antenna and a power-delivery coil. The relay station, which itself also contains an 802.11n transceiver, commands the chip using a customized UWB protocol managed by the on-chip controller, which is responsible for packetizing (depacketizing) the data to (from) the relay station from (to) implant. The data link center frequency is 4 GHz and uses on-off-keying (OOK) modulation with 1.5-ns-long pulses. The relay station powering coil inductively couples to the on-chip power coil at 13.56MHz. The chip can record neural signals from 1024 electrodes simultaneously from any programmable rectangular region of 65,536 electrodes, amplifying the signal and digitizing it with an on-chip 10-bit successive-approximation-register (SAR) analog-to-digital converter (ADC) running at 8.68MS/s.

Circuit Configurations

Fig. 2 shows the analog front-end (AFE) circuitry and recording timing diagram. The MEA consists of 128 by 128 pixels where each pixel is capable of stimulation and recording from one or all of its four electrodes. Stimulation is biphasic with three bits of amplitude controlling up to 100µA per pixel. Pulse width of each phase, direction of current (anodic or cathodic), and active sites of stimulation are programmable. In recording mode at any given time, a programmable block of 16 by 16 pixels, giving access to 1024 electrodes, share a single programmable gain amplifier (PGA) and ADC. This recording block can be reprogrammed every 100µs. The four electrodes at each pixel can be dynamically multiplexed at 8.5kS/s, or one of the four can be selected to achieve 4× oversampling. Row and column addressing of the recording pixel block can either be contiguous or separated by a fixed interval. Signal amplification and filtering inside each pixel relies on integrate, sample, and reset operation [1] that provides anti-aliasing low-pass filtering with an effective cut-off frequency of 3.5kHz. Each pixel supports chopping for offset rejection and flicker noise reduction. Pixel outputs are shared per column, which connects to a 128-to-1 column multiplexer, followed by a two-stage switched-capacitor track-and-hold PGA and an inter-

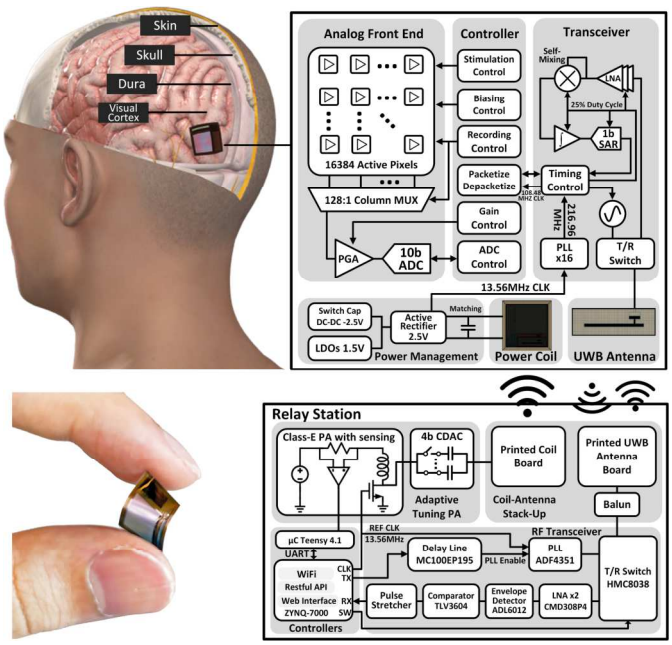

Fig. 1 System block diagram, including (bottom left) demonstration of post-processed, mechanically flexible implant.

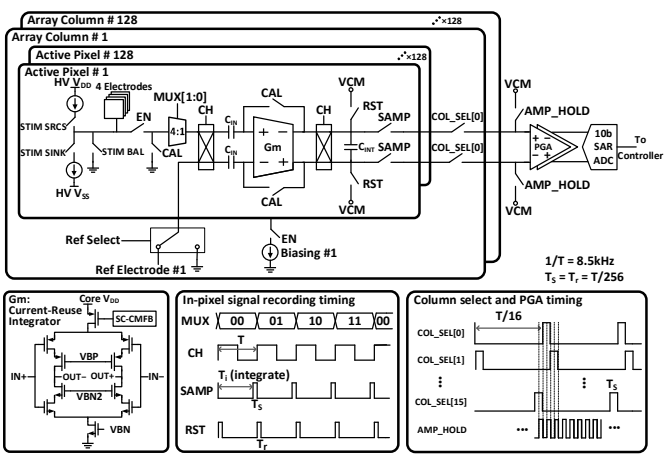

Fig. 2 AFE schematic and recording timing diagram.

leaving 10-bit SAR ADC. Ten samples of digitized data are grouped into a 125-bit packet for data telemetry where non-data bits are used for synchronization and error correction.

Measurements and Conclusions

The transceiver TX and RX data rates are 108Mbps and 54Mbps, respectively and use a single on-chip antenna with time-division duplexing using a transmit/receive (T/R) switch. A duty-cycled differential LC voltage-controlled oscillator (VCO) is used for the transmitter, which has peak output power of 10dBm and energy efficiency of 50pJ/bit. The receiver includes a low noise amplifier (LNA), self-mixing double-balanced mixer, baseband integrator, and one-bit SAR ADC. After power on, the timing control unit starts duty-cycling the LNA, mixer, and integrator at a 54-MHz, 25% duty cycle, achieving energy efficiency of 200pJ/bit. The reference clock

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for the on-chip phase-locked loop (PLL) is extracted from the 13.56MHz power link. Fig. 3 (top) shows measurement of a packet transaction and OOK symbol '1'.

Wireless power transfer (WPT) relies on inductive coupling to the on-chip coil in the two top-level metals. Fig. 3 (middle) shows measurement of coil-to-coil link voltage gain and its equivalent power transfer efficiency. Fig. 3 (bottom left) shows transient measurement of each power domain, where the received RF power is first converted to the high-voltage (HV) V_{DD} (nominal 2.5V) through an active rectifier, and then converted to HV V_{SS} (nominal -2.5V) and Core V_{DD} regulated to 1.5V. Because of its coil-to-coil alignment dependency, HV V_{DD} is periodically read out by command from the relay station, allowing adjustment of the power delivered. Fig. 3 (bottom right) shows thermal measurement of the implant surrounded by ambient air, demonstrating 37 °C operation even in this unrepresentatively poor thermal environment.

After the foundry CMOS process, the chip is post-processed wafer scale to replace the top electrode metals with TiN, to thin the substrate to less than 15µm of silicon, and to passivate the topside with polyimide and the backside with parylene. Laser dicing is used to singulate the implanted chips. Fig. 4 shows wireless, *in vitro* characterization of the stimulation and recording in 1×PBS. The pixel array contains a single shorted-input pixel from which input-referred noise is measured to be 8.7µVrms in fully multiplexing mode, and 4.3µVrms in oversampling mode integrated from 10 to 4kHz. In-pixel gain is 35.5dB with a standard deviation of 1.04dB. Overall system gain can be tuned from a two-bit configurable PGA and has a range of 57 to 72dB. Biphasic current stimulation is verified with amplitude and pulse length modulations.

Fig. 5 shows wireless local field potential (LFP) recordings from different portions of the MEA implanted subdurally in the porcine model. Fig. 5 (left) shows an example of a high spatial density recording from a contiguous 16 by 16 pixels, while Fig. 5 (right) shows selected recordings covering the entire extent of the array. Since no existing design matches all the functions presented here, Fig. 6 compares component functions with other recent published results [2-4]; a die photo with blocks labeled is also shown.

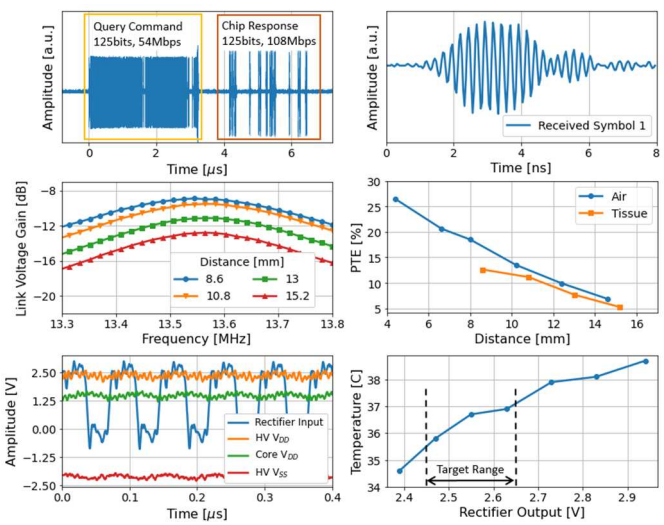

Fig. 3 Data telemetry and WPT measurement results: (top) OOK data transmission, (middle) coil-to-coil link voltage gain and power transfer efficiency, (bottom) on-chip power domains and thermal characteristic.

Acknowledgements

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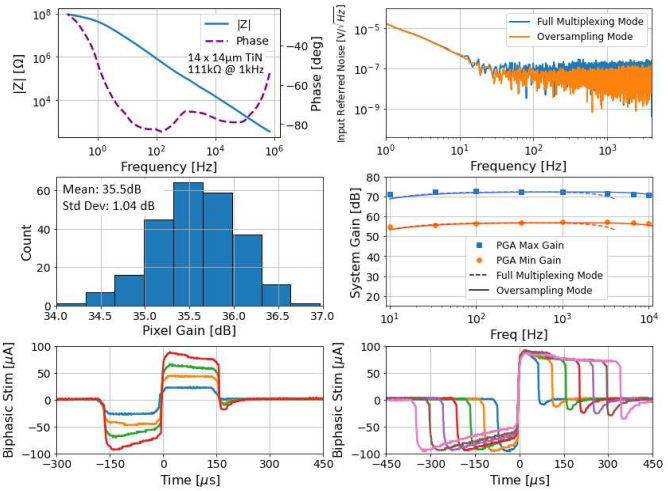


Fig. 4 *In vitro* wireless AFE measurement results: (top) EIS of electrode, input-referred noise spectrum, (middle) pixel gain and full system frequency response (bottom) biphasic stimulation with amplitude and temporal modulation.

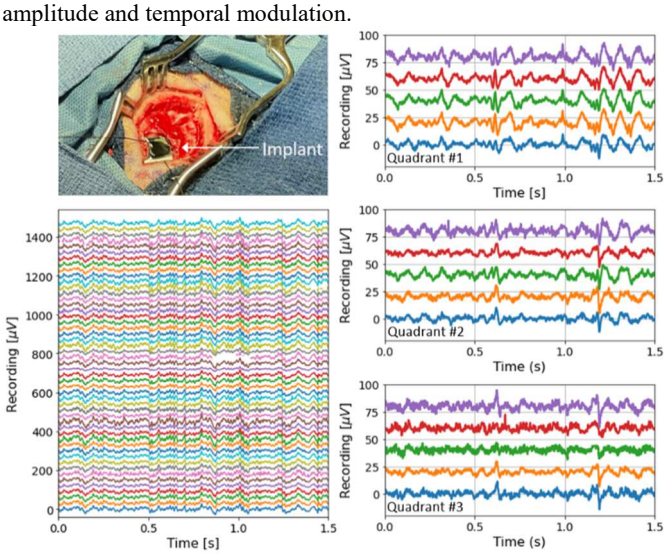
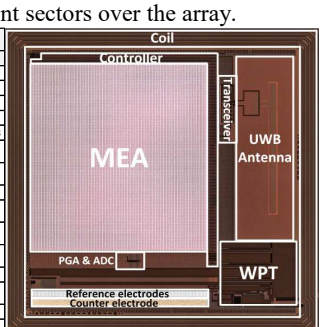


Fig. 5 *In vivo* wireless recording from porcine model: (left) subdural implant photo and recording from contiguously programmed pixels, (right) recordings from three different sectors over the array.

Publications	This Work	ISSCC'22 Lee [2]	ISSCC'20 Jia [3]	VLSI'21 Yoon [4]
Process [nm]	130	110	350	65
Chip Size [mm²]	144	4	15	20
Thickness [µm]	25	-	-	-
Flexible	Yes	No	No	No
# of Channel	16384/65536*	4	16	1024
Supply Voltage (V)	1.5,2.5,-2.5	2.3	1.8,3.3,4.0	2.5,1.8,-1.8
Power link Type	Inductive Resonance	Body-coupled	Inductive Resonance	-
Power link frequency	13.56MHz	32MHz	13.56MHz	-
Power [mW]	38.8	0.64	20.7	24.7
Data link Type	UWB-IR	Body-coupled	TX:OOK RX:Inductive	-
Data rate [bps]	TX:108M RX:54M	TX:20.48 M	TX:6.78M RX:50k	-
Energy per bit (pJ/bit)	TX:50 RX:200	32	-	-
ADC resolution [bits]	10	-	10	10
Simultaneous Recording [Channels]	256/1024*	4	16	1024
Sampling Rate [kHz]	34/8.5*	-	25	20
Recording Gain [V/V]	708-3981	-	562-3162	411-2661
Input Referred Noise [µVRMS]	4.3/8.7* (10-4kHz)	6.6	3.46	8.98 (300-10kHz)
HP Corner (Hz)	5	-	1-100	5/300
Max. Stim. Current (mA)	1	-	0.775	0.6



*With 4 to 1 Electrode Multiplexing

Fig. 6 Performance summary in comparison with prior work and die photograph.

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