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Highly Doped Polycrystalline Silicon Microelectrodes Reduce Noise in Neuronal Recordings *In Vivo*

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Abstract

The aims of this study are to 1) experimentally validate for the first time the nonlinear current-potential characteristics of bulk doped polycrystalline silicon in the small amplitude voltage regimes (0–200 μV) and 2) test if noise amplitudes (0–15 μV) from single neuronal electrical recordings get selectively attenuated in doped polycrystalline silicon microelectrodes due to the above property. In highly doped polycrystalline silicon, bulk resistances of several hundred kilo-ohms were experimentally measured for voltages typical of noise amplitudes and 9–10 k Ω for voltages typical of neural signal amplitudes (>150–200 μV). Acute multiunit measurements and noise measurements were made in $n = 6$ and $n = 8$ anesthetized adult rats, respectively, using polycrystalline silicon and tungsten microelectrodes. There was no significant difference in the peak-to-peak amplitudes of action potentials recorded from either microelectrode ($p > 0.10$). However, noise power in the recordings from tungsten microelectrodes (26.36 ± 10.13 pW) was significantly higher ($p < 0.001$) than the corresponding value in polycrystalline silicon microelectrodes (7.49 ± 2.66 pW). We conclude that polycrystalline silicon microelectrodes result in selective attenuation of noise power in electrical recordings compared to tungsten microelectrodes. This reduction in noise compared to tungsten microelectrodes is likely due to the exponentially higher bulk resistances offered by highly doped bulk polycrystalline silicon in the range of voltages corresponding to noise in multiunit measurements.

Index Terms

Brain implants; brain prosthesis; brain-machine interface; neural prostheses

I. Introduction

There is a critical need for technology to accurately and reliably sense electrical activity of single neurons *in vivo* for the success of several emerging brain prosthesis technologies [1]. Extra-cellular electrical signals recorded from single neurons in the brain range from several tens of microvolts to several hundred microvolts making such recordings very sensitive to noise both in short-term and long-term, chronic experiments. The quality as measured by signal-to-noise ratios (SNRs) and reliability of such single neuronal recordings using current technologies under long-term implantation conditions is often poor. The implantable microelectrodes currently used to record from single neurons are primarily made of metals such as platinum/iridium, tungsten, gold, stainless steel, etc. Noise reduction is primarily achieved using signal conditioning circuitry in the computer-based data acquisition system. Advanced signal processing algorithms have therefore been necessary and are commonly used to reduce noise and enhance signal quality in electrical recordings from single neurons. More recent approaches to enhance SNRs have also focused on decreasing the electrical impedance of the interface between the recording electrode and the brain tissue by enhancing the effective surface area of the electrode [2], [3]. However, chronic *in vivo* studies demonstrate that a decrease in impedance is not necessarily accompanied by a concomitant decrease in noise amplitudes in a consistent manner [2]. There are several likely sources of biological noise since the ionic conduction in the tissue is characterized by noise generated due to the stochastic nature of binding/gating in ion channels and ion-exchange pumps in the cell membranes, asynchronous and random ionic movement in the extra-cellular space due to electrical potentials generated by other cells in the vicinity of the recording electrode, mechanical micromotion of the tissue due to vascular pulsations, respiration etc., random thermal motion of the ions in the extra-cellular space, etc. A recent study has also suggested that neuronal adhesion at the cell-chip junction could significantly contribute to the Nyquist noise seen in neuronal recordings [4]. Almost all of the sources (except the thermal motion of the ions in the extra-cellular space) are active biological sources.

The other major source of intrinsic noise is the thermal noise in the implanted bulk conductors/doped semi-conductors where the conduction is electronic as opposed to the ionic conduction in the brain tissue. The Johnson–Nyquist formula for noise spectral density is useful for predicting noise power in these passive structures. In addition to thermal noises in the bulk of the conducting electrode, other possible sources of electronic noise that appear in the multiunit recordings are noise in the head-stage amplifier, preamplifier and the amplifiers. Other external sources such as fluorescent lighting, movement artifacts, electromagnetic interference, etc., can further add to the measured noise in multiunit recordings. However, with careful experimental preparation the above external noise sources can be greatly minimized.

In our earlier studies, we had reported the novel use of polycrystalline silicon as a material for sensing electrical activity from single neurons *in vivo* [5]–[7]. Unlike metals commonly used in recording electrodes, the bulk conduction properties of highly doped polycrystalline silicon is nonlinear in the range of voltages comparable to electrical signals from single neurons in the brain. The above property raises the exciting possibility that by selectively offering higher impedance to voltages in the range of noise amplitudes typically recorded using microelectrodes, polycrystalline silicon recording interfaces can selectively attenuate noise *in situ* compared to the commonly used metal based recording interfaces. Unlike prior approaches to noise reduction that focused on roughening the surface of the recording electrode the current study focuses on modulating the bulk conduction properties of the recording electrode.

A. Theory

Conduction in polycrystalline silicon mainly takes place by carrier motion from one grain to another by tunneling and/or thermionic emission through the barriers at the grain boundaries. For highly doped semiconductors, the Fermi level is close to the conduction band and the voltage drop across the depletion zone in the grain is very small. Almost all of the applied external voltage is dropped across the grain boundary itself. According to the model proposed by Doshchanov [8] and more recently used by Pentia [9] the relationship between current density j and applied voltage across multigrain semiconductors is given by

$$j = \frac{ev_0 n_0 \theta}{1 + \gamma} \exp\left(-\frac{V_1}{kT}\right) \left[1 - \exp\left(-\frac{eU}{kT}\right)\right] \quad (1)$$

where e is the electronic charge, v_0 is the average thermal velocity of the electrons, n_0 is the electron concentration, k is the Boltzmann's constant, and T is the absolute temperature. V_1 and V_2 are the voltages on either side of the grain boundary such that $V_1 - V_2 = eU$ and is given by

$$V_{2,1} = V_0 \left(1 \pm \frac{eU}{4V_0}\right)^2 \quad \text{where} \quad V_0 = \frac{Q_s^2}{8\varepsilon\varepsilon_0 N_D} \quad (2)$$

where Q_s is the trap density and N_D is the dopant density. U is the applied voltage across a grain-boundary and is given by: $U = V_{\text{app}}/N$ where V_{app} is the external applied voltage and N is the number of grain boundaries. Also ε is the absolute permittivity and ε_0 is the dielectric permittivity of the medium. The variable θ is defined as

$$\theta = D_n + \frac{v_R}{v_0} \quad (3)$$

where D_n is the diffusion coefficient of the electrons and v_R is the rate at which electrons are captured in boundary states and

$$\gamma = v_0(v_{d1}^{-1} + v_{d2}^{-1})\theta \quad (4)$$

where v_{d1} and v_{d2} are the effective diffusion rates of the carriers to the right and left of a grain boundary.

The unknown parameters are n_0 (carrier density), Q_s (trap density) and N_D (dopant density). For very high dopant densities, the carrier density is essentially same as the dopant density. The only other unknown parameter (Q_s) can be obtained by minimum mean squares method (explained later in Section III). Using a doping concentration of $10^{21}/\text{cm}^3$, estimated optimal trap density of $1.6 \times 10^9/\text{cm}^2$ (detailed later in Section III), dimensions of the microelectrode ($50 \mu\text{m} \times 4 \mu\text{m}$ cross section), and the measured grain size of approximately 60 nm the low voltage I - V characteristics of doped polycrystalline silicon as predicted by the above model in (1) is plotted in Fig. 3 (in comparison with experimental measurements). The I - V plot in Fig. 3 can be differentiated into two distinct regions. An initial high resistance region at extremely low voltages ($< 25 \mu\text{V}$) is separated from a low resistance region at higher voltages ($> 150 \mu\text{V}$). The region of the current-potential characteristic having a higher resistance corresponds to the "compensation region" [10] where the lowering of the intercrystallite barriers caused by the longitudinal electric field is offset by an additional capture of electrons by boundary states [8]. Alternately, the low resistance region

corresponds to a “decancellation regime” in which the filling depends weakly on the applied voltage, and an additional capture of electrons by boundary states no longer compensates for the lowering of the barriers caused by the electric field [8]. Similar carrier transport models have also been proposed by Mandurah *et al.* [11] in the past. However, such differential resistance behavior in polycrystalline silicon predicted by the model for applied voltages in the range spanning a few microvolts to hundreds of microvolts has not yet been tested experimentally. Interestingly, differential resistance behavior has been experimentally verified in high doped polycrystalline silicon thin films under high applied voltages (~30–50 V) [12].

In this study, we first experimentally verify the differential resistance behavior in doped polycrystalline silicon at voltages comparable to signals and noise typically recorded in multiunit recordings. We then investigate if the bulk semiconducting properties of polycrystalline silicon lead to noise reduction in electrical recordings from single neurons *in situ*.

II. Methods

A. Polycrystalline Silicon Microelectrode Fabrication

The polycrystalline silicon microelectrode shanks used in our experiments were fabricated using the SUMMiT-V (Sandia’s Ultra-planar, Multilevel MEMS Technology) process. This is a sacrificial surface micromachining process with multiple polycrystalline silicon layers as mechanical/electrical layers and silicon dioxide as the sacrificial material and the complete processing has been discussed elsewhere [5]–[7], [13]. The process consists of alternating layers of n-type, fine grained, ultra-low stressed polysilicon films and silicon dioxide layers. The polysilicon is deposited from silane using low-pressure chemical vapor deposition (LPCVD). The sacrificial oxide layers are deposited using LPCVD from tetraethylorthosilicate (TEOS). The shanks consisted of two layers of polysilicon films that were phosphorus doped to $10^{21}/\text{cm}^3$ and were $50\ \mu\text{m} \times 4\ \mu\text{m}$ in cross section and approximately 5 mm long.

B. I–V Characterizations of Bulk Polycrystalline Silicon

Current-potential characterizations were performed using two probes (Model 4440, MC Systems) in a shielded probe-station mounted on a vibration free table and attached to a microscope (Microzoom, Bausch and Lomb). The probes were externally connected to an Agilent 1500A semiconductor parametric analyzer using triaxial cables. The microelectrodes were adhered to $100 \times 100\ \mu\text{m}$ square gold pads using conducting epoxy and two-point *I–V* measurements were performed. The probes from the probe-station touched the gold pads and not the polycrystalline silicon microelectrode (to protect the microelectrode from getting shattered due to inadvertent application of force from the probes). With a step size of $25\ \mu\text{V}$ precise current measurements were made over a $25\text{--}2000\ \mu\text{V}$ range on two different polycrystalline silicon microelectrodes (three repeat measurements from each microelectrode). Current densities were determined by dividing the measured current values by the cross sectional area of the microelectrode ($50\ \mu\text{m} \times 4\ \mu\text{m}$).

C. Estimation of Grain Sizes in the Bulk Polycrystalline Silicon

Grain size measurements were carried out under tapping mode AFM (Molecular Imaging, Phoenix, AZ) through the lineal intercept technique [14]. In this technique, lines are drawn on the photomicrograph, and the number of grain-boundary intercepts, N_l , along a line is counted. The mean lineal intercept is then

$$\bar{l} = \frac{L}{N_l M} \quad (5)$$

where L is the length of the line, M is the magnification of the photomicrograph of the material. If the grains are spherical, the diameter of the grains could be calculated by the following equation [15]:

$$D = \frac{3}{2} \bar{l}. \quad (6)$$

D. In Vivo Recordings

All procedures were carried out with the approval of the Institute Animal Care and Use Committee (IACUC) of Arizona State University, Tempe. The experiments were performed in accordance with the National Institute of Health (NIH) guide for the care and use of laboratory animals (1996). All efforts were made to minimize animal suffering and to use only the number of animals necessary to produce reliable scientific data.

Multiunit recordings from both tungsten and polycrystalline silicon microelectrodes were tested in a total of eight different adult Wistar rats. Polycrystalline silicon and tungsten microelectrodes were implanted separately in $n = 3$ animals each to record both multiunit neuronal signals and noise. In addition, there were two other animals which were implanted with both polycrystalline silicon and tungsten microelectrodes at approximately the same depth and location with respect to the bregma but approximately 1 mm apart in the anterior–posterior axis. One of animals that was implanted with both microelectrodes was overdosed with anesthesia and clinically dead. Electrophysiological recordings were made from the clinically dead animal in order to determine the electrical noise values in the absence of biological activity. No unit activity (only noise) was recorded from the two animals implanted with both tungsten and polycrystalline silicon microelectrodes.

The tungsten microelectrodes (FHC Inc., Bowdoinham, ME) had a shank diameter of 125 μm with a tip taper of 20° and epoxylite insulation. The polycrystalline silicon microelectrodes had a shank width of 50 μm and tip tapers of approximately 19°, 28°, and 53° and were insulated with epoxylite [6]. A micrograph of the insulated tungsten and polycrystalline silicon microelectrode is shown in Fig. 1. Both microelectrodes were insulated with the same epoxy, and have comparable thickness. The polycrystalline silicon microelectrodes were bonded to a silver wire using conducting epoxy. A gold connecting pin was soldered to the other end of the silver wire. A custom made printed circuit board (PCB) was made and consisted of an Omnetics connector (NPD-AA-16, Omnetics Corp., Minneapolis, MN) and two gold female pin connectors. A stainless steel ground wire was soldered onto the circuit board as well.

The animals were induced using a mixture of 50 mg/ml ketamine, 5 mg/ml xylazine, and 1 mg/ml acepromazine administered intramuscularly (0.1 ml/100 g body weight). Each animal was attached to a stereotaxic frame (Kopf Instruments, Tujunga, CA). Two craniotomies were performed using a hand held drill for the ground and working electrodes. The craniotomy for the ground electrode was performed on the opposite hemisphere. The craniotomy for the microelectrode was centered approximately 3 mm lateral and 2 mm post-bregma. The dura was removed prior to electrode insertion via a dura pick. The PCB was then mounted on the stereotaxic frame with the appropriate microelectrode. The microelectrodes were slowly inserted in the brain at a rate of approximately 10 $\mu\text{m/s}$. The

microelectrodes were implanted at a depth of approximately 1.5 mm using a micromanipulator with a linear step resolution of 10 μm .

E. Data Collection/Analysis

Neural recordings were obtained using a 16-bit multichannel recording system (TDT Inc., Alachua, FL). Spontaneous neural recordings were obtained on the day of the implant, while the animals were lightly sedated. The neural recordings were sampled at 12 kHz and bandpass filtered from 300–3000 Hz, with a gain of 1000. Raw data and individual spikes were recorded. When the signal amplitude was larger than three times the standard deviation of the amplitude distribution in the raw data, it was saved in a separate file associated with potential spikes or signals and when the signal amplitude was less than three times the standard deviation of the amplitude distribution it was considered noise. Three 1-min segments were recorded from each animal with the corresponding electrodes. The spike waveforms were converted and transferred to Offline Sorter (Plexon Inc., Dallas, TX) for further analysis. The spikes were sorted using a valley-seeking sorting mechanism that is based on principle component analysis. Peak-to-peak (P2P) voltage levels were exported and calculated for each spike and unit.

A probability density function (*pdf*) of the amplitude distribution was obtained from each of the three noise recordings per electrode to analyze the distribution of noise levels in polycrystalline silicon and tungsten electrodes. The *pdfs* were obtained by dividing the range of amplitudes into 20 equally spaced bins. A Gaussian fit was then applied to the *pdfs* to obtain the standard deviations (SD) of the noise *pdf*. The square of the SD was then used as an estimate of the noise power. A *t*-test with 95% confidence interval (CI) was performed to determine the level of significance in the comparison between levels of noise power in the data recorded using tungsten and polycrystalline silicon microelectrodes.

F. Impedance Measurement

The impedance of each electrode was tested *in vivo* by a three-electrode method using an electrochemical workstation (CH Instruments Inc., Austin, TX). The counter and reference electrode were both made of stainless steel wire similar to [15]. Both the reference and counter electrodes were implanted in the brain at locations several millimeters away from working electrode. Voltage was applied between the reference and the working electrode whereas current was measured between the counter and the working electrode. Voltage amplitude of 5 mV and frequency between 100 Hz–100 kHz was sampled. None of the microelectrodes were biased, and all of the impedance measurements were stable as confirmed by repeat measurements. Bode and Nyquist plots of the impedance of the tungsten and polycrystalline silicon microelectrodes were plotted and compared. Three impedance readings were taken from each of the $n = 4$ polycrystalline silicon microelectrodes and each of the $n = 3$ tungsten microelectrodes. Impedance measurements were not taken from the devices implanted in the clinically dead animal.

III. Results

I–*V* measurements across the bulk polycrystalline silicon microelectrode at small voltages confirm the nonlinear relationship as shown in Fig. 2(a). The error bars in the *I*–*V* measurements of Fig. 2(a) represent the maximum and minimum of the sample values for all six readings; the mean is represented by the points. The resistance at 25 μV was found to be 74 k Ω which decreases to a steady-state value of approximately 9 k Ω at voltages higher than 200 μV . The polycrystalline silicon microstructure shows small equiaxial grains of size 60 nm as determined by tapping mode AFM (Molecular Imaging, Phoenix, AZ) and shown in Fig. 2(b). The mean of the current-potential curves was fit to the physical model [8]

described by (1) and the best fit was determined by iterating through a series of trap density values and generating mean squared errors over the entire range of voltages for each of the trap densities. The best fit was determined by choosing the trap density value with the minimum mean squared error. It was observed that a trap density of $1.6 \times 10^9/\text{cm}^2$ resulted in a minimum mean square error (R^2) of 5×10^{-8} . Simulated current-potential characteristics using the above trap density in the model described by (1) is overlaid on experimentally determined values in Fig. 3 demonstrating good fit. The simulated physical model with the best fit was then used to estimate bulk polycrystalline silicon resistance values for voltages below $25 \mu\text{V}$ for which experimental current measurements were not feasible using commonly available semiconductor parametric analyzers and the high precision Agilent 1500 A used in this study.

Multiunit recordings with repeatable unit activity were seen in $n = 6$ animals using polycrystalline silicon ($n = 3$) and tungsten microelectrodes ($n = 3$). From each animal three 1-min recording segments were made for a total of 18 recording segments where spontaneous multiunit activity was observed. In the 18 recording segments there were a total of 61 distinct units (neurons) identified after sorting. The polycrystalline silicon microelectrodes recorded 27 units while the tungsten microelectrodes recorded from 34 units. The average peak-to-peak amplitudes and the standard deviation in the amplitudes of each unit are shown in Fig. 4 for all 61 units. The signal levels are arranged from smallest to largest mean peak-to-peak amplitude values. The red lines represent units recorded by the polycrystalline silicon microelectrodes while the black lines represent those from tungsten microelectrodes.

The overall average signal levels (mean $\pm$ std. dev.) were $98.2 \pm 72.6 \mu\text{V}$ and $91.8 \pm 46.8 \mu\text{V}$ for the polycrystalline silicon and tungsten microelectrodes, respectively. A student t -test showed no significant difference ($p > 0.10$) between the population of mean spike amplitudes recorded using polycrystalline silicon microelectrodes and those recorded using tungsten microelectrodes as shown in Fig. 4. Probability density functions of noise amplitudes in recordings from polycrystalline silicon ($n = 4$ animals including one animal with both polycrystalline silicon and tungsten microelectrodes) and tungsten microelectrodes ($n = 4$ animals including one animal with both polycrystalline silicon and tungsten microelectrodes) are shown in Fig. 5(a). A Gaussian probability density profile fit the probability density functions in all cases with a root mean square error of 0.002 for the mean probability density function of noise from polycrystalline silicon and 0.006 for that of noise from tungsten microelectrodes. The variance of the noise recorded using tungsten microelectrodes was significantly different ($p < 0.001$, using t -test for two samples with unequal variances) from the variance of the noise recorded using polycrystalline silicon microelectrodes as shown in Fig. 5(b). The typical RMS amplitude of noise in multiunit recordings obtained using the polycrystalline silicon microelectrodes was $2.9 \pm 0.1 \mu\text{V}$ that was significantly different ($p < 0.001$, using a student t -test) from that of the tungsten microelectrodes ($5.9 \pm 1.2 \mu\text{V}$). The rms noise amplitude obtained using polycrystalline silicon microelectrode was comparable to the rms noise of the data acquisition amplifiers (manufacturer's specifications, Medusa Pre-amps, TDT systems Inc., Boca Raton, FL) used in this study indicating that noise in the multiunit data recorded using polycrystalline silicon was largely due to the amplifiers themselves.

The electrochemical impedance spectra for polycrystalline silicon (average of three measurements each from $n = 4$ implants for a total of 12 spectra) and tungsten microelectrodes (average of three measurements each from $n = 3$ implants for a total of nine spectra) are shown in Fig. 6. The Bode magnitude plot was similar for both microelectrodes, as shown in Fig. 6(a). There were significant differences in the Bode phase plot only for frequencies greater than 10 000 Hz as shown in Fig. 6(b). The corresponding Nyquist plots

in Fig. 6(c) show that the curve for polycrystalline silicon microelectrodes is shifted to the left, but has similar slope compared to the curve for tungsten microelectrode. Typical raw multiunit data and high resolution tracings of background noise from each animal are shown in Fig. 7. The noise amplitudes in the multiunit recordings obtained from polycrystalline silicon are perceptibly lower than those obtained using the tungsten microelectrodes. Finally, noise recordings from an animal with both polycrystalline silicon and tungsten microelectrodes that was overdosed with anesthetic and clinically dead are shown in Fig. 8(a). The probability density functions of the noise amplitudes [Fig. 8(b)] are similar to those recorded from live animals shown in Fig. 5(a). The corresponding variances of noise from both polycrystalline silicon and tungsten microelectrodes are only marginally smaller than the corresponding variances of noise shown earlier in Fig. 5(b).

IV. Discussion and Conclusion

The central goal of this study is to test if the exponential increase in bulk resistance in polycrystalline silicon at lower voltages effectively attenuates smaller amplitude noise signals in multiunit recordings. The nonlinear I - V conduction properties of doped polycrystalline silicon at low voltages ($< 150 \mu\text{V}$) had been theoretically predicted by earlier studies [8], [10], [11], but to our knowledge have been experimentally confirmed for the first time in this study using a high-precision semiconductor parametric analyzer for voltages as low as $25 \mu\text{V}$. The theoretical model fits the experimental measurement using reasonable values for the trap densities which strengthens the validity of the models [8], [10], [11]. The repeatability of the measurements ($n = 3$ from each microelectrode) and consistency across two different polycrystalline silicon microelectrodes increases confidence in this characterization.

Selective attenuation of noise observed in the neuronal recordings caused by the high resistance of the polycrystalline microelectrode in the range of voltages corresponding to the noise amplitudes can be better understood using the illustration in Fig. 9. The electrical interface between the polycrystalline silicon recording site and the neuron can be modeled using a series combination of electrolyte resistance ($R_{\text{electrolyte}}$ in Fig. 9) and a constant phase element (CPE in Fig. 9) [16]. The resistance offered by the bulk polycrystalline silicon is represented by R_{bulk} in series with CPE and can be modeled using (1). In a typical metal microelectrode based recording system, most of the neuronal signal and noise is captured by the internal resistance of the amplifier due to its relatively large value compared to the electrical impedance of the interface and R_{bulk} . For the polycrystalline silicon microelectrode, the interface impedance is mostly capacitive with a magnitude of approximately $1 \text{ M}\Omega$ at 1 kHz [16] and the bulk resistance, R_{bulk} for the neuronal signal (action potential amplitudes larger than $15 \mu\text{V}$) is $9 \text{ k}\Omega$ as obtained from the measured I - V characteristics. However, for noise amplitudes typically in the range of 0 – $15 \mu\text{V}$ *in vivo*, bulk resistance R_{bulk} of the polycrystalline silicon can now be estimated using (1) with doping concentration of $10^{21}/\text{cm}^3$, estimated trap density of $1.6 \times 10^9/\text{cm}^2$, the dimensions of the microelectrode ($50 \mu\text{m} \times 4 \mu\text{m}$ cross-section), and the measured grain size of approximately 60 nm and is found to be $1.1 \text{ M}\Omega$ at $5 \mu\text{V}$. For voltages smaller than $5 \mu\text{V}$, the bulk resistance increases exponentially beyond the estimated $1.1 \text{ M}\Omega$. Therefore, noise amplitudes are significantly attenuated at the amplifier input compared to noise amplitudes captured by the amplifier input in the case of metal microelectrodes.

Peak-to-peak amplitudes of the individual neuronal units were predictably similar in recordings from both polycrystalline silicon and tungsten microelectrodes, as shown in Fig. 4. Similarity in the distributions of peak-to-peak amplitudes seen in Fig. 4 and the fact that the recordings were obtained from similar locations in rodent somatosensory cortices indicates that the overall transduction of single neuronal activity (or signal) in both tungsten

and polycrystalline silicon were similar. Similarities in the electrochemical impedance magnitudes and phases shown in Fig. 6 over the range of frequencies of interest in multiunit recordings further confirm this possibility. On the other hand, the significantly smaller variance in the noise recorded using the polycrystalline silicon compared to the tungsten microelectrodes (Fig. 5) using the same data acquisition systems and similar experimental conditions indicates a selective attenuation of the noise amplitudes in bulk polycrystalline silicon. Since the attenuation using polycrystalline silicon microelectrodes is only amplitude dependent, even signal components with amplitudes below few tens of microvolts (as is possible with local field potentials) are likely to be attenuated. However, the signal amplitudes (or action potentials) in multiunit recordings are discrete and there is a clear delineation in the amplitude scale between the noise and signals that allows for selective attenuation of noise. Therefore, the current-potential characteristics of polycrystalline silicon do not perceptibly change the shape of recorded action potentials but can potentially change the shape of recorded local field potentials due to selective attenuation of low amplitude components in the signal.

If the electrode–electrolyte interface impedance or the input impedance of the amplifier is much larger than the maximum resistance of bulk polycrystalline silicon, then the noise “filtering” effect of polygrain semiconductors would become negligible since only a small fraction of the sensed voltage will get dropped or applied across the bulk polycrystalline silicon regardless of the amplitude. In such a situation, the noise power levels of the electrical signal recorded using a polycrystalline silicon microelectrode will be similar to that of a metal microelectrode. The ability to attenuate noise also depends on the voltage (approx. 200 μV in Fig. 2) in the current-potential characteristics of polycrystalline silicon beyond which the bulk resistance is constant. The above voltage depends on the material properties of the polycrystalline silicon such as the grain-size, grain-boundary width, doping, and trap-density at grain boundaries as given by (1) and (2). Though the first three parameters can be controlled to an extent by varying the doping and annealing conditions, it is not feasible to change trap-density in a controllable fashion. However, changing some of the processing conditions could conceivably increase the slope of the nonlinear portion of the I - V curve at low voltages and resulting in even higher impedance and hence attenuation for voltage levels typical of noise.

Interestingly, noise traces shown in Fig. 8 from the clinically dead animal reveals only a marginal decrease in the noise amplitudes and variance for both polycrystalline silicon and tungsten microelectrodes. This indicates a lack of significant noise contribution from active biological sources (such as action potentials from neurons distant from the recording site) to the overall noise recorded by the microelectrodes. Root mean square amplitude of noise in the recording from tungsten microelectrodes continues to be significantly higher (range of 5–7 μV) than the root mean square amplitude of noise in the amplifier itself (manufacturer’s specification of 3 μV rms noise) while the corresponding value for the polycrystalline silicon microelectrodes was still approximately 3 μV . Since there was no significant difference in the recordings done in a fully enclosed grounded Faraday cage (data not shown), differentially coupled electro-magnetic interference (EMI) or other exogenous noise sources are unlikely to be the reason for the larger noise amplitudes seen in the tungsten microelectrodes. In addition, since thermal noise power is directly proportional to the real part of the impedance of the bulk conductor [17], thermal noise power in tungsten microelectrodes is expected to be smaller (the bulk resistance of tungsten is typically smaller than the steady-state bulk resistance of 9 k Ω seen for polycrystalline silicon). However, the contribution from thermal noise to the overall noise power is likely to be small due to the small lengths of the conductors involved and as indicated by the smaller noise powers in the polycrystalline silicon recordings. It is likely, therefore that the major sources (other than the amplifiers themselves) of the noise seen in these recordings are nonactive biological sources

in the tissue (such as random thermal motion of ions in the extra-cellular space, etc.) that lie outside the electrode and in the brain. The noise from these sources appears to then get selectively attenuated as it gets transduced by the polycrystalline silicon microelectrode.

The size of the recording site in the polycrystalline silicon microelectrode was not controlled in this study. The epoxylite insulation at the tip of the microelectrode was carefully wetetched until the electrochemical impedance of the recording site was approximately 1 M Ω at 1 kHz. The polycrystalline silicon microelectrode tips had three different taper angles of 19°, 28° and 53° and hence the dimensions of the recording site etched out of the epoxylite in each case will be different. One could also conceivably accomplish similar attenuation of noise by incorporating highly doped polycrystalline silicon in the conducting pathway of a signal recorded using a conventional metal microelectrode instead of using polycrystalline silicon microelectrodes.

In conclusion, we have demonstrated that the intrinsic differential resistance properties of polygrain semiconductors may offer a novel way to significantly reduce noise and hence improve SNR when recording low amplitude neuronal signals. However, such an improvement largely depends on optimizing the current-potential characteristics of the polygrain semiconductors, input impedance of the recording amplifier and electrode-electrolyte interface impedance.”

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Fig. 1. Micrograph of the (a) Tungsten microelectrode and (b) Polysilicon microelectrode after insulation. The scale bar represents 50 μm .

Fig. 2.

(a) Current voltage characteristics of the polysilicon shank averaged over six measurements. The error bars represent standard deviation in the measurements. The bulk resistance stabilizes to a constant value of approximately $9\text{ k}\Omega$ for voltages higher than $150\text{ }\mu\text{V}$. (b) AFM image of polysilicon shanks doped (by phosphorous) to $10^{21}/\text{cm}^3$ shows grain sizes to be approximately 60 nm.

Fig. 3.

Illustration of the best fit ($R^2 = 0.99$) between the experimentally measured current-potential characteristics and the theoretical physical model [described by (1)] at a trap density of $1.6 \times 10^9/\text{cm}^2$.

Fig. 4.

A catalog of mean (indicated by squares for polycrystalline silicon and diamonds for tungsten microelectrodes) and standard deviation (indicated by the error bars) of peak-to-peak amplitudes of 61 units recorded from six different animals three of which were implanted with one polycrystalline silicon microelectrode each and the other three were implanted with one tungsten microelectrode each. Data shown in red are peak-to-peak amplitudes of 27 units recorded using polycrystalline silicon microelectrode and those in black are peak-to-peak amplitudes of 34 units recorded using tungsten microelectrodes. No significant differences in amplitudes of the units were discernible.

(a)

Noise Power Comparision

(b)

Fig. 5.

(a) Probability density functions of amplitudes of noise recorded using tungsten ($n = 4$ animals; shown in black) and polycrystalline silicon ($n = 4$ animals; shown in red) microelectrodes. The units of amplitude along the x -axis are in microvolts. (b) Comparison of the noise powers in the electrical recordings obtained using tungsten (shown in blue) and polycrystalline silicon (shown in brown) microelectrodes.

Fig. 6.

Bode (a) magnitude and (b) phase plots of the mean (and standard deviation) electrochemical impedance of the polycrystalline silicon ($n = 4$ animals, shown in red) and tungsten ($n = 3$ animals, shown in black) recording sites. The electrochemical impedances are comparable in magnitude over all frequencies and in different animals while the phase of the electrochemical impedance is higher for polycrystalline silicon for frequencies greater than approximately 3 kHz (corresponding to 3.5 on the log-frequency scale). (c) Nyquist plot of the mean electrochemical impedance of the polysilicon (red) and tungsten (black). The curve for polycrystalline silicon is shifted to the left but the slope is comparable for both microelectrodes.

Fig. 7. Multiunit recordings from seven animals using tungsten and polycrystalline silicon microelectrodes are compared at two different time scales (same amplitude scales). The noise amplitudes from polycrystalline silicon microelectrodes are consistently smaller than the noise amplitudes from tungsten microelectrodes.

Fig. 8.

(a) Recordings of noise using tungsten and polycrystalline silicon microelectrodes from one animal that was overdosed in anesthesia and clinically dead show similar noise trends, as seen in Fig. 7(b). The variance of the probability density functions of the noise amplitudes from tungsten and polycrystalline silicon are only marginally smaller than the corresponding variances seen in live animals Fig. 5(a) indicating that the noise contributions from active biological sources such as action potentials from distant neurons were small.

Fig. 9.

Illustration of a microelectrode placed alongside a single neuron and the equivalent electrical circuit model between the point of entry of the neuronal signal into the microelectrode and the output of a recording amplifier. R_{bulk} is the resistance offered by the bulk polycrystalline silicon and can be modeled using (1). R_{bulk} is selectively large for voltages in the range of values corresponding to noise amplitudes typically seen in multiunit recordings. $R_{\text{electrolyte}}$ in series with a CPE models the interface between the polycrystalline silicon recording site and the neuron. R_i models the input impedance of the amplifier.