Published in final edited form as:

IEEE Trans Neural Syst Rehabil Eng. 2007 June ; 15(2): 227–234. doi:10.1109/TNSRE.2007.897027.

Finite Element Analysis of a Floating Microstimulator

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Abstract

Analytical solutions for voltage fields in a volume conductor are available only for ideal electrodes with radially symmetric contacts and infinitely extending substrates. Practical electrodes for neural stimulation may have asymmetric contacts and finite substrate dimensions and hence deviate from the ideal geometries. For instance, it needs to be determined if the analytical solutions are adequate for simulations of narrow shank electrodes where the substrate width is comparable to the size of the contacts. As an extension to this problem, a “floating” stimulator can be envisioned where the substrate would be finite in all directions. The question then becomes how small this floating stimulator can be made before its stimulation strength is compromised by the decrease in the medium impedance between the contacts as the contacts are approaching each other. We used finite element modeling to solve the voltage and current profiles generated by these radially asymmetric electrode geometries in a volume conductor. The simulation results suggest that both the substrate size and the bipolar contact separation influence the voltage field when these parameters are as small as a few times the contact size. Both of these effects are larger for increasing elevations from the contact surface, and even stronger for floating electrodes (finite substrate in all directions) than the shank-type electrodes. Location of the contacts on the floating electrode also plays a role in determining the voltage field. The voltage field for any device size and current, and any specific resistance of the volume conductor can be predicted from these results so long as the aspect ratios are preserved.

Keywords

Microelectrodes; neural stimulation; volume conductors

I. Introduction

Electrical stimulation is currently used as a treatment method in a number of disorders of the central and peripheral nervous system and being investigated for many new applications [1]-[7]. Many of these applications demand very localized activation of the neural tissue to produce functional results. In order to achieve this high spatial selectivity, microelectrodes with penetrating shanks into the neural tissue have been developed [8]-[10]. One of the major challenges of chronically implanted electrodes with penetrating shanks is the mechanical stress and the resulting chronic tissue response induced by the constant movement of the electrode and the tethering of interconnects. The tethering problem can be solved by replacing the interconnects with telemetry, both for powering the device and controlling the stimulus parameters. An example of such a wireless, floating device in the

peripheral nervous system is the BION stimulator that is controlled by radio-frequency electromagnetic waves [11]. Because the telemetry and power circuitry are incorporated into this stimulator, the smallest device size is in the order of several millimeters and therefore it is only suitable for activation of peripheral nerves and muscles. The use of ultrasound waves for energy transfer to a piezoelectric stimulator has also been proposed to eliminate interconnects [12]. This device does not contain electronic circuits for storing power or shaping the stimulus pulse. The stimulator is not small enough again for central nervous system applications. To achieve the level of spatial selectivity needed in the central nervous system, the device needs to be in the submillimeter range while being able to inject sufficient current for neural stimulation. Our group is pursuing a novel floating microstimulator design that uses optical means for energy transfer [13]-[15]. Because the stimulator is essentially a semiconductor photodiode without any active circuitry that requires continuous power for storing the stimulus current or controlling its waveform parameters, the device can be made in the micrometer range.

We leave the issue of transferring sufficient energy into a floating, implantable microstimulator to another report. In this paper, our main objective is to find an ideal device geometry and contact parameters that will maximize the voltage field in the volume conductor. Maximization of the stimulation strength will in turn allow us to reduce the device size. The first question that we are posing, therefore, is how small can a floating device be made before its stimulation strength is compromised because of the medium impedance? It should be noted that the stimulator is assumed to be a constant current source. A floating device by definition is a bipolar stimulator because both contacts carrying stimulating and return currents have to be on the device. As the size of the stimulator is being reduced and hence the bipolar contacts are approaching each other, it is expected that the output voltage will eventually start to decrease. That is, the medium impedance between the bipolar contacts will decrease as the intercontact distance is reduced; as a result of which the output voltage will begin to decay since the stimulator is a constant current source. There will be a lower limit on the device size below which stimulations to activate a nearby neuron.

In general, spatial profile of the potential field determines the volume of activation in the surrounding neural tissue. If we achieve our goals, the size of the stimulator will be comparable to the targeted neural structures. The field strength will drop quickly by distance from a bipolar stimulator of such a microscale and thus the spatial extent of the extracellular voltage that is of significant amplitude will also be in micrometer range. Because we cannot ignore the radial component of the potential gradient inside the axon at this scale, the activation function formulated by Rattay *et al.* for myelinated and unmyelinated axons is not applicable in this case [16]. In order to simplify the formulation for activation function in this paper, we will only target myelinated axons and assume that the extent of the voltage field will be smaller than one internodal distance. In this case, only one node of Ranvier, that is closest to the cathodic contact, will experience the voltage generated by the stimulator. The simplification is that the depolarization at this node of Ranvier will be proportional to the extracellular voltage immediately outside the cell membrane. Thus, we will use the cathodic contact voltage itself and the potential field in the vicinity of this contact as the activation function rather than its second spatial derivation [16].

Analytical models have been developed to predict the voltage field for simple electrode geometries such as a sphere in an infinite medium or a disk electrode at the border of a semi-infinite medium [17]. Because of the difficulty in finding analytical solutions to more complex electrode geometries, several groups have used finite element (FE) analysis [18]-[23], or employed experimental methods [24]. In this study, we used the FE method to analyze the voltage fields for shank-type and floating microelectrodes. A step-by-step

approach was taken to advance the electrode geometry from a simple circular contact on an infinite substrate to a floating microstimulator. The objective was to study the effect of each geometrical parameter separately. These parameters included the substrate width, the choice of the contact shape, the intercontact separation, and the location of the bipolar contacts on a floating stimulator. It should be mentioned that some of the electrode geometries were tested purely for investigational purposes and not as an attempt to simulate practical neural electrodes. In most cases, the plots were normalized with the voltage amplitudes of the simple electrodes with infinite substrates. Preliminary results of this study were published in abstract form [13]-[15].

II. Methods

A. Software and System Parameters

The MemETherm module was selected in CoventorWare software package for this static FE analysis. A uniform mesher setting was used for all electrode models. A finer mesh size was selected for the contacts than the volume conductor and the substrate. The algorithm adjusted the mesh size wherever needed, particularly at the edges and corners, to minimize errors. The “extruded linear brick” option (with *Pave* algorithm) was chosen for the element type, which partitions the domain into convex subdomains until the mesh size specified in the element field is satisfied. Each mesh element was transformed locally onto a rigidly defined master element, and Poisson's equation was approximated linearly across the element. The simulations were performed on an Intel Pentium 4 processor based personal computer with a speed of 2.6 GHz and a RAM memory of 512 MB. The maximum number of mesh elements was kept under 500 000 to obtain results within five hours depending on the configuration. The results were viewed through Tecplot, the visualizer tool of CoventorWare.

B. The FE Model

The FE model included a 100- μm -thick, laminar, nonconductive substrate placed half way in the middle from the bottom surface in a cubic volume conductor Fig. 1(a). Monopolar or bipolar contacts (1 μm thick) were embedded on the top surface of the substrate in the middle and leveled with the surface. Fig. 1(b) shows the monopolar electrode model that consisted of a circular contact with a radius of 11.3 μm and a substrate extending wall-to-wall in the volume conductor, simulating an infinite substrate. Fig. 1(c) shows the shank-type electrode with a monopolar contact where the substrate width was made finite in the *y* direction. Fig. 1(d) shows a floating electrode with a finite substrate in all directions. The volume conductor dimensions were $1000 \times 1000 \times 1000 \mu\text{m}$ for the infinite substrate and shank-type electrodes [Fig. 1(b) and (c)] and $500 \times 500 \times 500 \mu\text{m}$ for the floating electrode Fig. 1(d).

A 1- μA current is applied to the bottom surface of the stimulating contact in all cases. For the bipolar configuration, the return current ($-1 \mu\text{A}$) was injected into a second contact symmetrically positioned on the substrate. For the monopolar electrodes with infinite substrates, a layer of metal (15 μm thick) was placed on top of the volume conductor as a return electrode and a negative 1 μA was applied Fig. 1(b). For the shank-type monopolar electrodes, where the substrate does not extend to the borders of the volume conductor, another return electrode with similar properties was placed on the bottom of the volume conductor and the return current was split evenly between the top and bottom return electrodes to ensure symmetry in the model Fig. 1(c). All metal contacts had a specific resistivity of $2.2 \times 10^{-6} \Omega \text{ cm}$ to simulate a highly conductive metal. The specific resistance of the medium was chosen as 300 $\Omega \text{ cm}$ to simulate the gray matter in the central nervous

system [25]. The voltage fields in the volume conductor were symmetrical for anodic and cathodic contacts.

III. Results

A. Voltage Profiles for Monopolar Electrodes

Voltage fields generated by square and circular contacts were simulated and compared with the analytical solution reported by Wiley and Webster for the circular geometry [17]. The potential calculated with the analytical formula differed from that of the FE analysis by 3.3% at the surface for a circular contact of $11.28\ \mu\text{m}$ radius (66.37 versus 64.16 mV, respectively). The voltage for a square contact of the same area ($20 \times 20\ \mu\text{m}$) was 60.65 mV, 5.5% less than the circular case. Fig. 2(a), (b), and (c) show the decline in the potential in all three directions. Each trace is normalized by the voltage at its own contact surface. In Fig. 2(a), the voltage decay is slightly slower with the square contact compared to the circular one. In Fig. 2(b), the decline is much faster in the y direction as the substrate is made narrower. All plots decline in the same order in the z direction in Fig. 2(c) but without being affected much by the substrate width. In the z direction, the voltage begins declining immediately above the surface.

B. Effect of Substrate Width

The effect of substrate width on the voltage field was studied for monopolar, square electrodes ($20 \times 20\ \mu\text{m}$). The substrate was first extended to the borders of the volume conductor horizontally to simulate the infinite case, and then reduced to simulate the shank type electrodes. The voltage decay was slightly faster in all three directions, but particularly in the y direction [widths 60 and $30\ \mu\text{m}$ in Fig. 2(a), (b), and (c)]. In Fig. 2(d), the voltage at the center of a square contact is plotted as a function of substrate width [geometry as in Fig. 1(c)] for increasing elevations from the surface. Note that each plot is normalized by the monopolar voltage measured at that elevation point with an infinite substrate. The voltage decreases first slowly as the width is decreasing and sharply when the substrate size becomes comparable to the size of the contact. The decline is faster for higher elevations above the contact. For example, the voltage is at 80% of the maximum at a width of $60\ \mu\text{m}$ for $z = 20\ \mu\text{m}$. The 80% point is already crossed at a width of about $87\ \mu\text{m}$ for $z = 30\ \mu\text{m}$. Another way of looking at these plots is that narrowing of the substrate starts affecting the field potential at higher elevations first and works its way down. Overall, these results show that the effect of the substrate width on the voltage field becomes significant only when it is as small as a few times the contact size.

C. Bipolar Electrodes: Contact Separation

The effect of intercontact separation was investigated for square contacts on an infinite substrate in Fig. 3(a). The bipolar voltages measured between the contact centers for practically infinite contact separation and infinite substrates were 121.3, 72.0, 45.5, 32.6, and 25.9 mV at elevations of $z = 0, 10, 20, 30$, and $40\ \mu\text{m}$ from the surface, respectively. These values were used to normalize the plots in Fig. 3(a) at corresponding elevations. Thus, all traces in Fig. 3(a) converge to 1.0 at far right. As the intercontact distance was reduced, the potential on the device surface dropped down to 80% of the maximum bipolar value at the intercontact distance of $45\ \mu\text{m}$. The rate of decline was faster at increasing elevations from the surface ($z = 0$ to $40\ \mu\text{m}$).

D. Floating Stimulators

The effect of contact separation was studied for a floating electrode in Fig. 3(b) with the geometry shown in Fig. 1(d). The device length was varied together with the contact

separation while the margins around the contacts from the edge of the device were kept at $10\ \mu\text{m}$. The same values were used for normalization, as in Fig. 3(a). For this floating electrode geometry, the 80% of the maximum occurred at an intercontact distance of $63\ \mu\text{m}$ at the device surface ($z = 0$), which is 40% larger than the separation obtained for an infinite substrate ($45\ \mu\text{m}$). The rate of voltage decrease was faster at increasing elevations from the surface, similar to the effect of substrate width shown in Fig. 2(d). The decrease by elevation was stronger for the floating electrode in Fig. 3(b) than the plots in Fig. 3(a).

E. Placement of the Contacts on Floating Stimulators

Several locations for the contacts on the floating stimulator were tested for maximization of the voltage field in the volume conductor. First, both anode and cathode were placed on top as shown in Fig. 4 and a current of $1\ \mu\text{A}$ amplitude was passed between the contacts. The device size was $40 \times 40 \times 100\ \mu\text{m}$. Each contact was $20 \times 20\ \mu\text{m}$ and thereby leaving a margin of $10\ \mu\text{m}$ around near the edges. The center-to-center contact separation was $60\ \mu\text{m}$. The potential profiles along the longitudinal lines passing through the electrode centers in the x direction Fig. 4(a) and the transverse lines passing through the anode center Fig. 4(b) were obtained at successive elevations of $10\ \mu\text{m}$ from the surface without normalization. The dash lines in the inlets show where the voltage profiles were extracted. The xyz reference system indicates the positive direction in each axis. The maximum anodic (or cathodic) potentials in the volume conductor were 48, 24, 12, 6.5, and 4 mV at elevations of $z = 0, 10, 20, 30$, and $40\ \mu\text{m}$, almost decreasing by half every $10\ \mu\text{m}$. The bipolar contact surface potential is about 79% of the value obtained with the infinite substrate (2×48 versus $121.3\ \text{mV}$). In Fig. 4(a), both positive and negative halves are slightly asymmetrical along the x axis since the voltage field of each contact is affecting that of the other due to their proximity.

Next, the contacts were moved to the walls at the ends and placed in the middle, while keeping the contact size and the stimulator dimensions the same (Fig. 5). The potential profiles in the z direction at successive elevations of $10\ \mu\text{m}$ from the device surface Fig. 5(a) and in the x direction at horizontally increasing distances from the center of the anode were plotted Fig. 5(b). The contact voltage was $52\ \text{mV}$, about 8.5% larger than the case in Fig. 4, where both contacts were on top. However, the voltage quickly decreased from this value at the top edge of the contacts [$z = -10\ \mu\text{m}$, Fig. 5(a)] to $15\ \text{mV}$ at $z = 0$, the top surface of the device, and further decreased to $8\ \text{mV}$, and $3\ \text{mV}$ at $z = 10$, and $20\ \mu\text{m}$, respectively. Note that the voltage peaks along the x axis occur slightly outside the edge at each end [Fig. 5(a), device length is $100\ \mu\text{m}$]. The voltage drop in the negative x direction from the anodic contact surface was initially faster than that of the stimulator in Fig. 4 in the z direction, but then slower after $20\ \mu\text{m}$ from the surface Fig. 5(b). The peak voltages were approximately 52, 23, 13, 9, and $6\ \text{mV}$ at $x = 0, -10, -20, -30$, and $-40\ \mu\text{m}$, where $x = 0$ is the anodic contact surface. This geometry is preferable if the targeted neural structures are near the end walls. But, the field is much weaker on the top surface compared to that of the stimulator in Fig. 4.

The contribution of the margins permitted around the contacts in Fig. 5 was investigated by reducing the size of the stimulator to $20 \times 20 \times 100\ \mu\text{m}$ and thereby allowing the contacts to cover the entire side walls (Fig. 6). The anodic (or cathodic) contact potential was $32.5\ \text{mV}$ (more than twice of what is measured on the top surface in Fig. 5(a) but much less than that of Fig. 4) and decreased to 11.8, and $6.6\ \text{mV}$ at elevations of $z = 10$ and $20\ \mu\text{m}$. In the x direction, the measurements were 17.4, 10.1, and $6.7\ \text{mV}$ at distances of $x = -10, -20$, and $-30\ \mu\text{m}$ from the contact surface in horizontally increasing distances. Thus, the voltage gradient in the horizontal direction was less than that of the vertical direction. The voltage amplitudes were larger in the z direction than what was measured in Fig. 5 ($32.5, 11.8$, and $6.6\ \text{mV}$ versus $15, 8$, and $3\ \text{mV}$), however, much less in the x direction ($32.5, 17.4, 10.1$, and

6.7 mV versus 52, 23, 13, and 9 mV) from the contact surface. So the margin around the contacts had a significant effect.

Lastly, the configuration in Fig. 7 was tested where one of the contacts was placed on the top while the other was etched into the end wall and centered in the middle as it was done in Fig. 5. The stimulator dimensions were switched back to $40 \times 40 \times 100 \mu\text{m}$. The voltage at the top contact was 46 mV and it decreased to 26.5, 15.0, and 9.5 mV at $z = 10, 20$, and $30 \mu\text{m}$ above the surface. Thus, the voltage gradient along the z axis was less than that of the device in Fig. 4 as a result of moving the cathode to the end wall and the amplitudes were comparable.

IV. Discussion

A. FE Model Versus Analytical Solution

The surface potential for a circular disk contact estimated by the FE model differed from the analytical solution reported by Wiley *et al.* [17] by 3.3%. This can be explained by inherent shortcomings of the finite element analysis. First, although the size of the volume conductor was made very large compared to the size of the contacts, it was still finite. The potential at the borders of the volume conductor was frequently checked to ensure that it was not more than a few percent of the contact surface potential. Increasing the size of the volume conductor would improve the accuracy of the model, but require a larger number of nodes and hence a longer calculation time. It took about 3 h to complete a simulation for a model with 400 000 nodes using the given computer hardware.

B. Circular Versus Square Contacts

The simulations on infinite substrates indicate that the contact voltage and thus the access impedance for a square contact is about 5.5% less than that of a circular one with the same area. This difference must be due to the shape factor. A rectangular electrode with a high aspect ratio may even have a smaller access impedance if this effect is due to the radial asymmetry. The shape factor may give the ability to the user to adjust the access impedance for different applications without changing the contact area.

C. Effect of Substrate Width for Shank Electrodes

The substrate width affects the potential field of the electrode as investigated for monopolar contacts in this report. The potential value reaches a maximum when the width of the substrate is infinite. The potential at the contact surface does not decrease significantly until the substrate width becomes as small as a few times the contact size. This is the point where the current that flows around the back of the device becomes significant. Before this point, the stimulation strength is not compromised if the targeted neural components are near the electrode surface. However, the voltage decline is larger for higher elevation from the surface Fig. 2(d). Therefore, the effect of substrate width is stronger at increasing heights from the contact center, even though the original value (the value with an infinite substrate) of the potential at higher elevations is much smaller than the surface to begin with. In summary, the effect of the substrate width for the shank-type electrodes increases by distance from the electrode surface.

D. Floating Electrodes

The contact voltage of a floating micro-stimulator can be in similar amplitudes to that of the monopolar electrodes on large substrates, so long as the device size is at least a few times larger than the size of the contacts and that some precautions are taken for the placement of the contacts. However, the substrate size has a stronger effect at increasing distances from the device surface Fig. 4(d), similar to the shank electrodes. This implies that the volume of

activation around the stimulator will be smaller for smaller substrates although the contact voltages will be comparable. Bipolar stimulation has the known advantage of being more local than monopolar electrodes. These results further suggest that the spatial extent of the stimulation effect can be varied by changing the substrate size as well as the separation between the contacts.

The contact potentials increase by 8.5% when they are moved from the top of the device to the end walls. However, the bipolar voltage at the level of the device surface is much less. This suggests that the contacts should be positioned on the surface that is nearest to the targeted neural structures for stimulation. For instance, if the bypassing axons near the top surface are targeted then the contacts should be placed on the top surface. The stimulator in Fig. 7 may be the optimum choice in this case with the cathode placed on the top surface and hence keeping it close to the neural structures to be activated above, and placing the anode on the end wall so that the device length is minimized. On the other hand, if the targeted neural structures are more likely to be near the end walls of the device, then both contacts can be placed on the end walls, as in Fig. 5.

Fig. 6 suggests that a margin around the contacts make a significant contribution to the contact voltage (52 mV when present versus 32.5 mV). The smallest width of this margin that results in an acceptable voltage loss should be determined to minimize the areas of the end walls.

Although specific units are given to the device dimensions in this study, the dimensional units cancel out with that of the specific conductance of the volume conductor. This can be appreciated from the analytical formula reported in the literature [17], although we have not derived similar equations here. Hence, the voltage field for any device size and current, and any specific resistance of the volume conductor can be estimated from these results provided that the aspect ratios are made similar to that of the geometries studied here. The calculated potentials would change inversely with the conductivity of the medium and the device dimensions. For anisotropic media, one can simply scale the coordinates in the plots with the scale factors formulated by Plonsey [26].

It should be noted that the models of this study do not account for the double-charge layer of the electrode-electrolyte interface. Inclusion of the interface capacitance into the model will introduce temporal variation to the voltage profiles. On the other hand, the resistive component of the interface tends to even out the current density across the surface especially at low frequencies [27]. The contribution of these resistive and capacitive components of the electrode-electrolyte interface to the spatial and temporal variations of the voltage field needs to be investigated.

We assumed myelinated axons with larger inter-nodal distance than the spatial extent of the voltage field for simplification. However, when targeted structures have arbitrary geometries, it is not only the amplitude but also the spatial distribution of the voltage that plays a role in activation. In this case, the stimulation efficiency of the potential fields simulated in this study should be evaluated with 3-D models that incorporate the excitation properties of the targeted neural structures.

Finally, the geometries studied here are meant to be general guidelines for microelectrode designs and hence may not always represent practical electrodes. Also, we did not limit ourselves to what can readily be realized with current microfabrication techniques for the interest of finding the ideal solution. For instance, the placement of the contacts on the side walls as in Fig. 7 may be difficult to implement. Using these results as general guidelines, other variations of the contact geometries should be investigated for practical electrode geometries.

V. Conclusion

The voltage at the surface of a monopolar contact varies as a function of the substrate width. The substrate width needs to be at least a few times the contact size to minimize the voltage loss, in which case analytical solutions for an infinite substrate can be used to predict the potential field. These results warrant the use of FE models for narrower substrates. Similar conclusions can be made for the bipolar electrodes. The differential voltage drops sharply for contact separations of less than two or three times the contact size Fig. 3(a). Both effects, substrate width Fig. 2(d) and contact separation Fig. 3(a), are stronger at increasing elevations from the electrode surface.

A floating stimulator with rectangular geometry generates the maximum bipolar voltage when the contacts are placed on the side walls. Reducing the device size does not result in a significant loss in the bipolar voltage output until it becomes comparable to the size of the contacts. The voltage drop is larger at increasing elevations from the device surface, an effect similar to that of the shank-type electrodes but stronger. Thus, the device size should be determined depending on how far the targeted neural structures are from the stimulator.

Acknowledgments

The authors would like to thank Dr. J. Schesser of the New Jersey Institute of Technology for reviewing and commenting on the manuscript.

Biographies

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S. S. Ur-Rahman, photograph and biography not available at the time of publication.

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Fig. 1.

Electrode geometries modeled in this study. Contacts are drawn relatively larger than they are to show details. A: the cubic shaped volume conductor is shown with the electrode geometry in C placed half way from the bottom. Figs. B, C, and D show various electrode geometries from the top view. B: a monopolar electrode on a substrate that extends to the borders of the volume conductor in the horizontal plane to simulate infinity. The electrode current ($1\mu\text{A}$) current is applied to the bottom surface of the metal contact embedded on the top surface of the substrate. The current returns through an electrode (thickness $15\mu\text{m}$) that covers the entire top surface of the volume conductor. C: finite width substrate (simulating shank-type electrodes) with a monopolar contact is shown. The return current is split in half between the return electrodes placed on the top and the bottom of the volume conductor for symmetry. For the bipolar case two contacts are placed symmetrically on the substrate. D: a floating stimulator is modeled. Two square contacts (each $20 \times 20\mu\text{m}$) are placed $10\mu\text{m}$ from each end symmetrically on the top surface. The positive current ($1\mu\text{A}$) is applied to one of the contacts and returned through the other. The device size is $40 \times 40 \times 100\mu\text{m}$. E: A sample 3-D voltage plot taken from the top surface of a floating microstimulator shows the details of the meshing structure.

Fig. 2.

The effect of contact shape and substrate width on the voltage field for monopolar electrodes. A: Potential profiles for circular and square monopolar electrodes in the x direction (see Fig. 1(b) for the geometry). All voltage profiles start at the contact center. The FE solution for a square ($20 \times 20 \mu\text{m}$) and circular ($r=11.28 \mu\text{m}$) contacts with the same area is plotted to demonstrate the effect of contact shape on the voltage profile. Analytical solution for a circular contact (radius= $11.28 \mu\text{m}$) on an infinite substrate is also plotted for comparison. B and C: Voltage profiles in the y and z directions for a circular contact on $60 \mu\text{m}$ and $30 \mu\text{m}$ substrates demonstrate the effect of substrate width. D: Potential fields for a single square contact at increasing elevations from its center ($z = 0$ to $30 \mu\text{m}$) as a function of the substrate width (see Fig. 1(c) for the geometry). Each trace is normalized with respect to its own maximum for an infinite substrate.

Fig. 3.

The differential voltage measured in the volume conductor due to bipolar contacts placed on A: an infinite substrate, and B: a floating electrode, as the distance between the contacts is varied. The voltage difference between the contact centers is plotted at elevations of 0, 10, 20, 30, and 40 μm from the surface.

Fig. 4.

Potential profiles along the x (A) and y (B) axes for a floating electrode. Inset shows the line positions at which the potentials are extracted, i.e., at incremental steps of $10\ \mu\text{m}$ starting from $z = 0$ at the contact surface. Black and gray squares are the cathodic and anodic contacts, respectively. The size of the microstimulator is $40 \times 40 \times 100\ \mu\text{m}$ and the contacts are $20 \times 20\ \mu\text{m}$.

Fig. 5.

Potential profiles along the x (A) and y (B) axes for a floating electrode where the contacts are placed on the end walls and centered in the middle of the wall. Insets show the line positions at which the potentials are extracted in each case, which are at $10\mu\text{m}$ incremental elevations from $z = -10\mu\text{m}$ to $z = 40\mu\text{m}$ in A ($z = 0$ is the contact surface), and at horizontally increasing distances from the contact surface in B ($x = 0$ to $x = -50\mu\text{m}$). The contact and device sizes are same as in Fig. 4.

Fig. 6.

Potential profiles along the x (A) and y (B) axes for a floating electrode where the contacts cover the entire walls at the ends. The stimulator size is reduced from that of Fig. 5 to $20 \times 20 \times 100 \mu\text{m}$. The potentials are extracted at $10 \mu\text{m}$ incremental elevations from $z = 0$ to $z = 50 \mu\text{m}$ in A, and at horizontally increasing distances from the contact surface in B ($x = 0$ to $x = -50 \mu\text{m}$).

Fig. 7.

Potential profiles along the x axis for a floating electrode with one contact placed on the side wall and the other on the top. The device size is $40 \times 40 \times 100 \mu\text{m}$. The potentials are extracted at $10 \mu\text{m}$ incremental elevations from $z = -10$ to $z = 40 \mu\text{m}$ where $z = 0$ is the contact surface.