SOLVING THE INTERCONNECTION PROBLEM OF FLEXIBLE MULTIELECTRODE ARRAYS BY USE OF ADDRESSABLE ORGANIC SEMICONDUCTOR STIMULATOR CELLS

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Abstract: Microimplantable devices like cochlear implants, pain killers, and deep brain stimulators have reached a high degree of reliability and usability for the patient. In contrast to this, implementation of neural stimulators with hundreds or thousands of microelectrodes is still hindered by the interconnection problem between the electrode array and the electronic stimulator device. Particularly when the mechanical flexibility needs to be preserved, interconnection of all electrodes of large 2D-array to a stimulator/recorder device is almost impossible, since a monolithically integrated circuit can only be attached to the electrode array's periphery, using either bumps or bonds. To overcome these limitations, in this contribution an addressable active stimulator cell is proposed, which can be fabricated either with printable long chain organic semiconductors or, as described here, with short chain semiconductors (oligomers) like Pentacene. These flexible semiconductor devices can be interlaced between the electrode rows and columns of arbitrarily sized and shaped 2D multicontact array, thus completely preserving the array's mechanical flexibility.

Introduction

Neural Stimulators like cochlear implants, pain killers, deep brain stimulators, and even first visual prostheses all have been developed in the last century by combining microelectrodes or multielectrode arrays and CMOS integrated stimulator circuits.

Although some of these microimplantable devices already have reached a high degree of reliability and usability for the patient, neural stimulation with hundreds or thousands of microelectrodes is hindered by several factors, including the limited capacity of miniaturized electrodes, high electrode impedance, sensitivity against harmful voltages exceeding the electrochemical potential window and particularly the interconnection problem between an application specific mechanically flexible electrode array and the monolithically integrated multichannel stimulator device. Flip Chip mounting or other techniques using bonds or bumps have shown to be suitable for smaller arrays but cannot provide the required interconnectivity for large arrays, since routing thousands of wires in between a 2D arrays of miniaturized electrodes is not possible. Other approaches, using flexible electrode arrays mounted on top of solid state devices, are limited in device shape or when several smaller solid state circuits are mounted to distinct positions within a larger structure, the systems become difficult to encapsulate and handle.

Materials and Methods

To overcome the limitations of these classical approaches, an addressable active stimulator cell is proposed which can be fabricated using organic semiconductor materials, incorporated between the layers of the mechanically flexible multicontact array.

The second major modification of the classical approach is switching from frequently used current sources to a voltage source approach [1]. Due to the high impedance of miniaturized electrodes and the limited supply voltage, current source transistors saturate and circuit complexity dramatically increases since active current regulation and monitoring is required. Under these conditions the voltage source approach can be implemented easier and because of its auto adaptive behavior it is much better suited for integration with todays organic semiconductor materials.

In contrast to highly optimized and well characterized CMOS processes, organic semiconductor processes are by far less standardized. Stronger parameter variations and even worse parameters like higher threshold voltages and 100 to 1000 times lower mobility are two reasons that make it difficult to build reliable flexible devices. To design the stimulator cell, the following parameters have been assumed for n-type and p-type organic semiconductors:

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- For n-type printable semiconductors threshold voltages of up to 5V and a mobility of 0.2 cm^2/Vs,
- for p-type threshold voltages of up to 2V and a mobility 1 cm^2/Vs,
- for PVD (physical vapour deposition) generated p-type pentacene layers, also a mobility of 1 cm^2/Vs has been used, even though higher mobilities of up to 35cm^2/Vs have been reported for pentacene single cristals,
- for printed organic semiconductors a 20µm design rule has been taken into account, as well as operation voltages of 10V and an on/off current ratio of 10^3,
- for pentacene layers a channel length of 2.5 to 20µm has been used and an on/off ratio of 10^5 can be reached as shown below.

Flexible stimulator cell

The mechanically flexible stimulator proposed here, can generate stimulation pulses from bursts of short pulses, similar to the switching regulator principle. A circuit diagram of the stimulator cell providiong the functionality of an adaptive waveform generator is shown in Figure 1. The timing diagram, shown in Figure 2, describes generation of biphasic biased pulses and the voltage monitoring process.

Here, for a short time of t<100µs (depending on the application), the power supply voltage is switched by M1 to the stimulation electrode output. Due to the high impedance of the electrode and tissue and an electrode capacitance of 10 to 100nF, the voltage can never exceed critical voltages in this first phase.

Any sequence of short pulses increases the electrode voltage rapidly at the beginning. Thus currents at the beginning are siginficantly higher than in current-source approaches, but intentionally limited by the w/l ration of M1 to a safe value because of the saturation of the OFET (organic field effect transistor).

When pulse generation continues, the electrode must be prevented from generating harmful voltages by monitoring the output voltage. Therefore after each pulse within the burst, the electrode is disconnected from the source for a current free measurement of the electrode voltage. So the actual electrode voltage can be compared to the reference voltage V_{ref} and the result state is saved in FF1. If the actual electrode voltage exceeds this reference voltage, the electrode remains disconnected until the electrode has discharged by a small amount and refresh pulses are enabled. In contrast to a constant current source, here major charge transfers only occur at the beginning of each pulse phase when electrode voltages are far below the critical limits.

Because of the circuit' ssymmetry, anodic first (by switching M1) or cathodic first (switching M2) pulses can be generated. To minimimize damage to the electrodes, biphasic pulses are generated, providing a charge balance on each electrode.

At the end of each pulse phase the reference voltage will be reprogrammed by a central control unit which is common to all stimulator cells, using the V_{ref} column line (Figure 1). The reference voltage is switched between $V_{ref}=V_{min}$ for the cathodic phase, $V_{ref}=V_{max}$ for the anodic-pulse phase, and $V_{ref}=V_{pause}$ for the pause phase between cathodic and anodic phase as well as for the pause phase between two consecutive biphasic pulses (Figure 2 left).

The pause phase between two biphasic pulses is used to complete the electrode's CV cycle. Since the current bursts are continued until the given reference voltage is reached, programming the reference voltage to $V_{ref}=V_{reset}$ at the end of each complete biphasic pulse cycle implements a re-biasing mechanism preventing

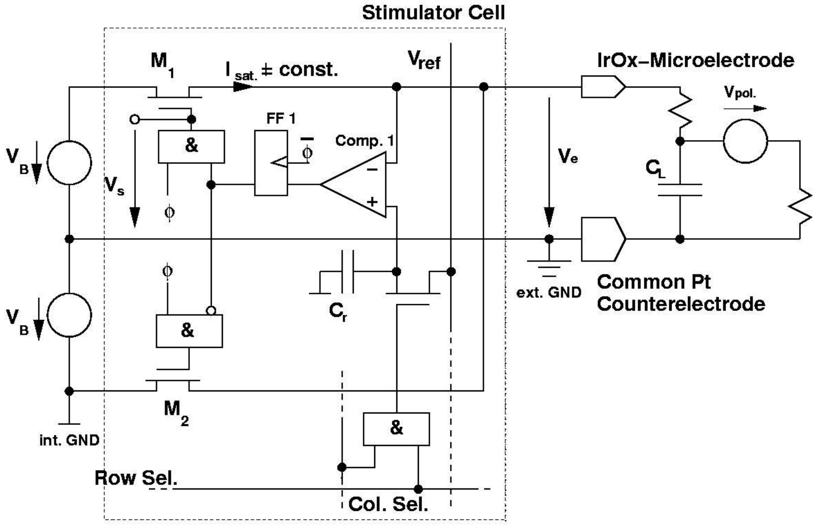


Figure 1: Schematic of the addressable stimulator cell, generating biphasic pulses according to a virtual ground

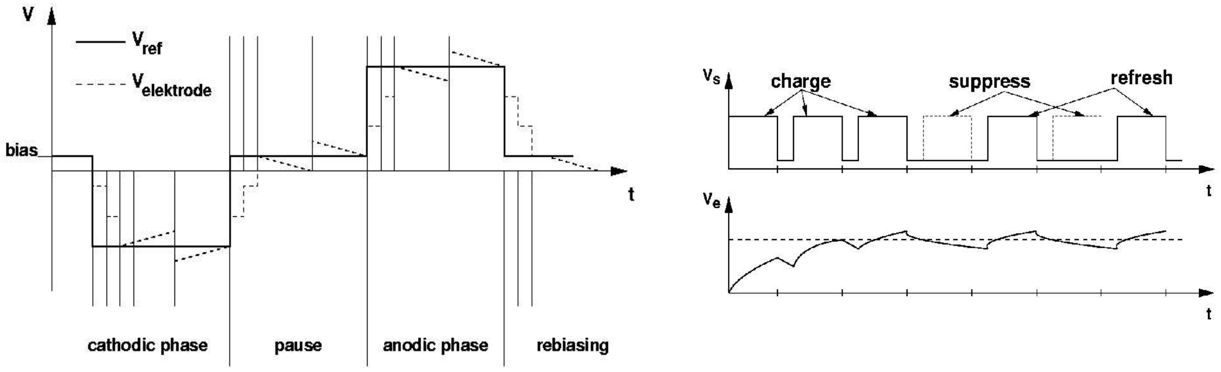


Figure 2: Timing diagram for an cathodic first biphasic pulse (left) detail of anodic phase electrode charing (right)

the electrode from polarization. For further improvement of the electrode's charge delivery capacity, the bias voltage V_{pause} and V_{reset} can be set to any value within 0V and V_{dd} (eg. 0.5V according to the virtual ground, as proposed in [2]).

Biphasic pulses can be generated from a single supply voltage, since positive and negative voltage bursts can be switched to the output, relative to virtual ground which is connected to a common indifferent counter-electrode (e.g. A Large Pt electrode). This greatly simplifies pulse pattern generation in large arrays, since passive channels no longer need to be used as current sinks.

Thus advantages and simplifications arising from this voltage based approach include:

1. independence from the highly variable current-voltage (CV) cycle of iridium oxide film electrodes [3],
2. limitation of the maximum and minimum electrode voltages to a safe electro-chemical potential window (e.g. $V_{min} = -0.6$ to $V_{max} = 0.8$ V),
3. avoidance of polarization of the electrode by an inherent rebiasing of the electrode after each biphasic pulse, which results in completion of the CV cycle,
4. continuous monitoring of the electrode in short current free phases, to control V_{min} and V_{max} (according to item 2) and for re-biasing (according to item 3),
5. reduction of power dissipation due to the use of a switching regulator principle instead of constant current sources,
6. single common counterelectrode to simplify switching of active channels in large arrays,
7. easy implementation of an optional binary recording of action potentials by reuse of already existing cell hardware [1].

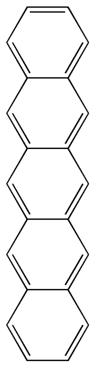
For integration of the device, the capacitance of C_r can be reduced to 100 fF and an area of approx. $10 \mu m^2$ since it is only discharged by the sampling transistor and the high impedance comparator (Comp. 1). Both switching transistors M1 and M2 are small compared to conventional programmable current sources.

Further developments include the design of a simple transcutaneous power and data transmission, which currently is still a CMOS device, but due to the ongoing development of 13.56MHz ISM-band organic devices for RFID applications can be replaced by an organic device in the future.

Pentacene based OFETs

As mentioned before pentacene, shown in Figure 3 is one of the most promising organic semiconductors [4,5,6,7,8]. Several research groups and companies are working with this material and extensive work has been carried out by the FhG-IPMS (Dresden). Major benefits of this organic semiconductor include:

Pentacene



1. is easy to handle,
2. can be purified by sublimation under vacuum,
3. can be applied in a physical vapour deposition (PVD) system,
4. has an excellent performance in organic field effect transistors (OFET),
5. is supposed to be non toxic,
6. is sufficiently stable.

Figure 3:Properties and chemical structure of Pentacene

The performance limits for single transistors are not reached yet, because there is still progress in device layout and material preparation and treatment.

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Currently the value of the charge carrier mobility in a single transistor is above 1 cm^2/Vs, the On/Off-ration is in the region of $10^{5,}$ and the threshold voltage is slightly negative. The drain current I_d of an organic thin film transistor in active regime is given by

$$I_d = \frac{W}{L}\mu\frac{\varepsilon_0\varepsilon_r}{d_{Ox}}[(U_{GS}-U_{th})U_{DS}-\frac{U_{DS}^{\ 2}}{2}] \quad (1)$$

with L = channel length, W= channel width, d_{ox}=thickness of dielectric, ε_r = dielectric constant, U_{GS} = gate-source voltage, U_{DS} = drain-source-voltage, U_{th} = threshold-voltage.

Substrates used for evaluation:

For evaluation of the performance of pentacene, it is necessary to have different test transistors and test patterns. In Figure 4 a cross-section of a pentacene based organic field effect transistor is shown.

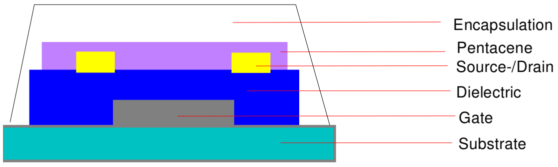

Figure 4: Cross-section of a bottom-gate OFET

To get more information about the behaviour of pentacene transistors and to demonstrate first circuits, the Fraunhofer IPMS developed test substrates containing transistors with different channel length and width, different dielectric thicknesses and some other variations. Two different test substrates are presented in Fig 5.

Besides of the layout of the substrates, the choice and treatment of materials has a strong influence on pentacene thin film growth and performance of the resulting devices and circuits [7]. To go one step further towards complex flexible devices organic dielectrics like polyimides have been integrated and are currently under evaluation.

The preparation of pentacene thin films can easily be performed by physical vapour deposition (PVD) techniques. Critical parameters are surface pretreatment, deposition rate, film thickness, substrate temperature and chamber pressure. Depending on the type of dielectric a oxygen-plasma cleaning-step leads to a better pentacene growth, especially if the dielectric is silicondioxide. The removal of water from the surface of the substrate by an annealing process is essential. Self-assembled monolayers like octadecyltrichlorosilane (OTS) for the silicondioxide or thiols for gold electrodes provides the most suitable surface for pentacene. The most effective pentacene film thickness is dependent on the dielectric thickness and its dielectric strength. If the thickness is too high, the applied field is not high enough to deplete the whole pentacene film. A low deposition rate (<0.01 nm/s) and a substrate temperature in a range of 50-70°C allows large crystals. To stabilize the device parameters, an encapsulation is necessary, which protects the device against water and oxygen.

Results

As mentioned before the performance of a pentacene transistor is strongly dependent on the preparation conditions. Figure 6 shows the electrical characterization of a transistor under ambient conditions. In this transistor the threshold voltage is much too high for a working device but the output characteristic exhibits a high current. In other devices, depending on their preparation conditions, lower currents in the range of µA have been found. The threshold voltage can be influenced by the surface

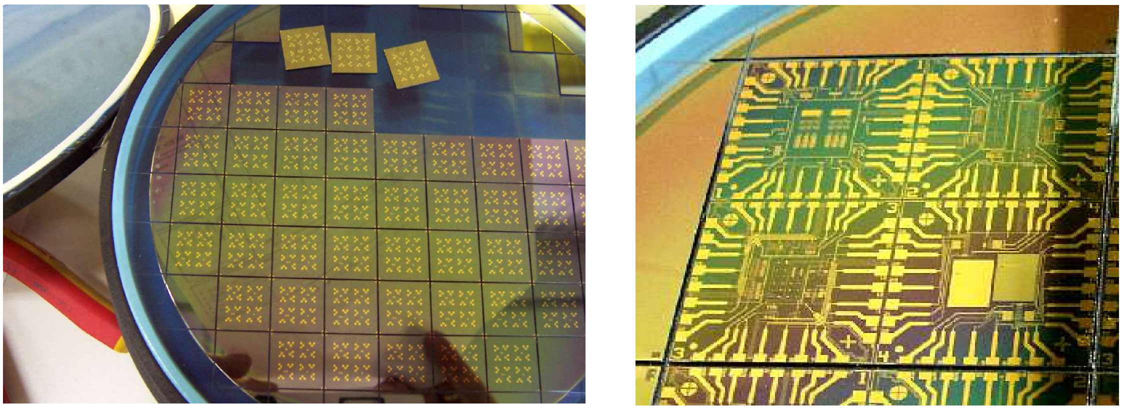

Figure 5: OFET Test Substrates: (left) Source/Drain: 30nm Au, L=2.5-20µm, W=10mm, with 0.5x0.5mm² contact pads, 16 transistors on a 1.5x1.5cm^2 substrate, 720 transistors on one Ø150mm Si-Wafer, the Wafer is used as the Gate and (right) Second Generation OFET circuit Substrates: Source/Drain: Au, Gate: structured Aluminum, 4 different blocks on a 5x5cm² substrate containing transistors, capacitors, ring-oscillators, EXORs, NANDs and other test patterns (FhG-IPMS)

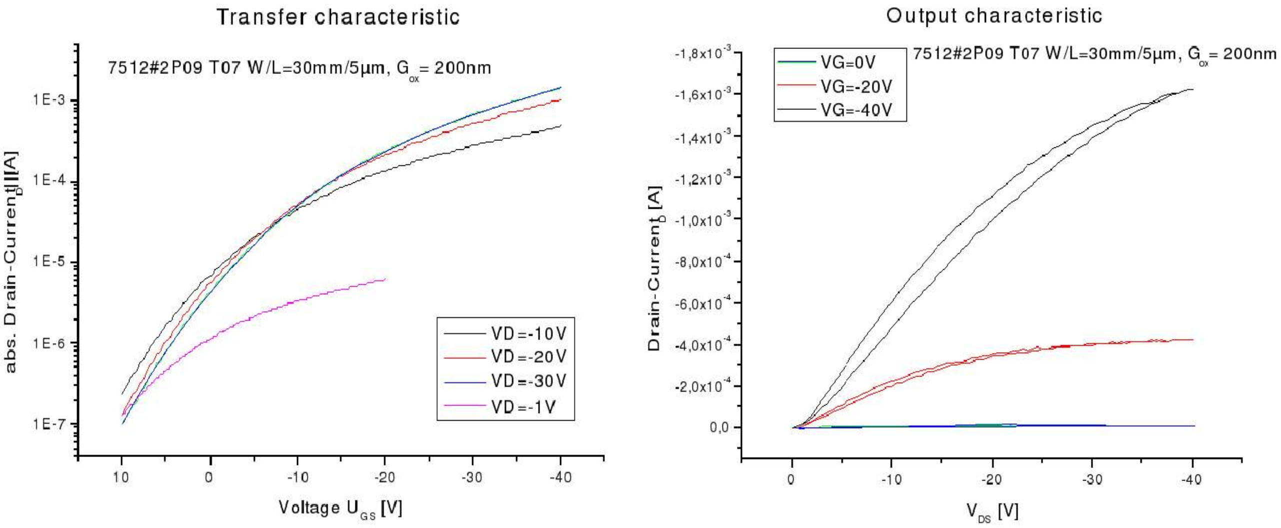

Figure 6: Transfer characteristic (left) and output characteristic (right) of an OFET on a second generation substrate

pretreatment and by the choice of materials. A shift in the threshold voltage can be observed under electrical stress in the presence of water and oxygen.

To demonstrate OFET circuits, seven and fiveteen stages ring oscillators have been prepared at the FhG-IPMS. These circuits have been realized on the second generation OFET circuit substrates. For these test structures 200nm Silicondioxide is employed as dielectric and an aluminium Gate-electrode has been structured. The achieved frequencies are well above 10 kHz, as shown in Figure 7.

For higher frequencies the thickness of the dielectric should be lower and an organic dielectric is favoured. One problem is the stability of the organic transistors; in ring oscillators for example, frequency range and voltage swing rapidly decrease under electrical stress and ambient conditions. Therefore an encapsulation of the devices is mandatory to acieve biostability. In view of the application as microimplantable device, both the encapsulations as well as the substrate have to be flexible. To realize this encapsulation it is possible to use foils, which can be laminated onto the flexible substrate. Another possibility for encapsulation is the use of a thin film coating e.g. Parylenes, applicable in a chemical vapour deposition (CVD) process [7].

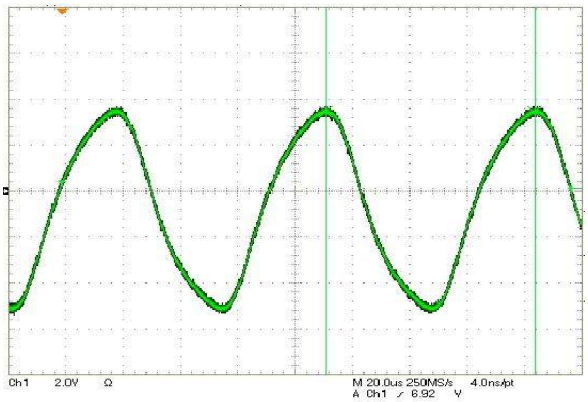

Figure 7: Ring-oscillator working at a frequency of up to 14 kHz and a voltage of 40V in darkness and 20V under air

To realize the stimulator cell described in Figure 1, which is intended to generate stimulation pulses of approx. 5ms from a burst of about 10 to 20 shorter pulses, a clock rates of 2-4kHz would be sufficient. According to the results presented above, clock rates of OFETs, even in the case of slightly higher circuit complexity, can reach several kHz. Thus the proposed stimulator cell design is suitable for transferring from an early CMOS implementation to mechanically flexible organic semiconductors.

Since circuit complexity and design rules of organic semiconductor materials do not allow building of digital to analog converters within each stimulator cell, the programmable reference voltage V_{ref} has to be stored on a capacitor, which can also be built from the organic dielectric between the Gate- and Source/Drain contact layers.

Conclusion

Pentacene based OFETs and organic circuits have already been fabricated successfully on silicondioxide. Currents required to drive the stimultators electrode's have been estimated at 0.1mA, which is achievable with today's pentacene transistors. Also switching frequencies of up to 10kHz are sufficient to generate pulses in the ms range and even below. Although it is also possible to use flexible substrates and coatings to build circits with pentacene as active layer, there are still open issues like long term parameter stability, quality and thickness of encapsulation materials, biostability and long term biocompatibility.

Besides the complex technological aspects, the simplicity of the stimulator cell allows further extensions for binary recording of action potentials, but such extensions will not be implemented in the ongoing design, which concentrates on the realization of the stimulator cell as a building block for large 2D-arrays. Also transcutaneous power and data transmission modules are based on proven CMOS designs and will not be developed here, but as an outlook, they might become available as organic devices too, because of the rapid development of printable RFID devices.

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