

Organic Electrochemical Transistors (OECTs) - Hands-on Experiment and Teaching Materials

Dustin Freimuth¹, Xuqiang Xu², Jana Zaumseil², Silvia Janietz¹, Amitabh Banerji^{1*}

¹University of Potsdam, Chemistry Education, Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany

²Heidelberg University, Institute for Physical Chemistry, Im Neuenheimer Feld 253, 69120 Heidelberg, Germany

*Corresponding author: abanerji@uni-potsdam.de

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Abstract Organic Electrochemical Transistors (OECTs) represent a cutting-edge technology with significant potential in healthcare, electronics, and environmental monitoring. This manuscript presents the development of a low-cost, hands-on OECT experiment designed for highschool education, bridging the gap between advanced research and classroom learning. The didactically tailored OECT prototype replaces complex fabrication methods with accessible materials, such as silver paste electrodes and drop-cast PEDOT:PSS, while maintaining functionality. The device operates as a switch, visualized through a propeller motor, and achieves an average ON/OFF ratio of 475. A pilot study with 12th-grade students demonstrated the experiment's robustness and educational effectiveness, with post-intervention knowledge tests revealing significant learning gains. Supplementary materials, including an animation and lab protocols, enhance understanding of OECT principles. The study underscores the feasibility of integrating modern research topics into curricula, paving the way for future developments like logic gates and expanded experimental kits. This work highlights the potential of OECTs as a tool for engaging students in organic electronics and fostering STEM interest.

Keywords: Curriculum Innovation, organic electronics, semiconductors, transistors, PEDOT:PSS

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1. Introduction

Organic electronics first caused a sensation in the 1970s when conjugated polymers could be converted into current-conducting materials by chemical doping. Since then, this field of research has expanded into all areas of electronics and led to the Nobel prize in chemistry in 2000 [1]. Organic electronics have found their way into everyday life as demonstrated, for example, by the integration of organic light-emitting diodes (OLEDs) in many modern displays [2]. Other electronic components such as transistors or solar cells, which are usually based on inorganic silicon, have already been recreated using organic alternatives [3,4]. Even if the efficiency of both technologies does not yet reach their silicon analogues, they are highly interesting both scientifically and economically [5]. The potential of organic electronics as a current and future technology also makes it relevant in a school context. However, the integration of new learning content into the school curriculum poses challenges for didactics, as integrated learning content has already been tried and tested for decades and has proven itself over time. The field of research that addresses precisely the problems of integrating cutting-edge research topics into the curriculum is "Curricular Innovation Research" [6]. We

have previously demonstrated successful curricular innovation on the topic of organic electronics. To teach organic electronics at a secondary school level, we have developed a teaching concept along with a material kit [7,8,9] containing materials to build and examine hands-on OLEDs and organic photovoltaic (OPV) devices in a low-cost approach without the usual requirements of a cleanroom or advanced lab facilities. However, the topic of organic transistors has not yet been addressed. This is desirable, as transistors are the most important electrical component in modern electronics (i.e. microprocessors) and thus, the understanding of their construction and function is of immanent importance.

In this article we present the development of a first prototype of an organic electrochemical transistor (OECT) for a hands-on teaching experiment, which has been tested with 12th grade highschool students. OECTs are a rapidly evolving technology with significant potential in healthcare, electronics and environmental applications. They can be used, for example, in biosensors [10], for neuromorphic computing [11], wearable and implantable electronics [12] and environmental monitoring [13]. This opens up several contexts in which OECT could be addressed in school. These include health and education, but also the latest inventions in science and technology. Both are subject areas that can be counted among pupils' favourite topics [14].

2. Scientific Background

Organic electrochemical transistors are a subgroup of organic transistors. Their basic function is to act as a switch or amplifier of currents or voltages. An organic transistor (as shown in Figure 1) consists of an organic semiconducting layer (the channel) between two electrodes (source and drain) that is separated from a third electrode (the gate) by an insulating dielectric. In case of an OEET this dielectric is replaced by an electrolyte containing mobile anions and cations (e.g. $\text{Na}^+(\text{aq})$ and $\text{Cl}^-(\text{aq})$). The source electrode is grounded and a small bias is applied between source and drain (drain voltage, V_D) to enable current flow. The carrier concentration or degree of doping of the organic semiconductor and thus the current flow through the channel (drain current, I_D) is modulated by the voltage applied between the source and gate electrode (gate voltage, V_G) [15].

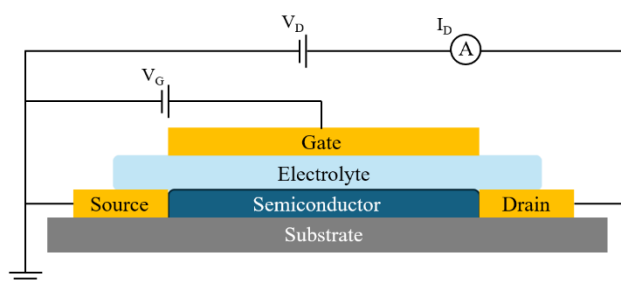


Figure 1. Schematic structure of an OEET with the gate electrode on top of the channel

In most OEETs the semiconductor is a conjugated polymer. When a gate voltage is applied, the electric field between the gate electrode and the channel leads to a penetration of ions into the polymer layer; anions for negative gate bias and cations for positive gate bias. To compensate these negative or positive ionic charges, holes or electrons are injected from the source electrode into the semiconductor, that is, the polymer is oxidized or reduced [16]. One may also view this the other way around, the polymer is oxidized or reduced due to the applied electrochemical potential (electrochemical doping) and the mobile ions compensate the excess charge in the polymer. Indeed, an OEET can be seen as an electrochemical cell, in which the working electrode is the semiconducting channel with the source/drain electrodes.

The presence of electronic charge carriers (holes or electrons) in the semiconducting layer enables current flow. As the gate voltage is varied, the charge carrier concentration (degree of doping) of the semiconductor changes and thus also the drain current. The current flow between the source and drain electrode depends directly on the width of the channel (W) and the distance between the two electrodes (channel length L). Since the entire volume of the semiconducting film in an OEET is doped (unlike a field-effect transistor), the thickness (d) of the semiconducting layer also contributes to the conductivity. The carrier concentration for a given gate voltage (V_G) is determined by the volumetric capacitance of the semiconducting layer (C^* , F/cm^3). The resulting current flow also depends on the charge carrier mobility (μ , $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$), which determines the velocity of charge carriers in an electric field given by the drain voltage (V_D). However,

typically the variation of drain current with the gate voltage ($\partial I_D/\partial V_G$, i.e. the transconductance g_m) is the more relevant parameter for OEETs as they are supposed to convert small voltage signals applied to the gate into large changes in the drain current. For high drain voltages the transconductance can be described by the equation (1) [17]:

$$g_m = \frac{\partial I_D}{\partial V_G} = \mu C^* \cdot \frac{W \cdot d}{L} \cdot (V_{Th} - V_G) \quad (1)$$

where V_{Th} is a threshold voltage. Importantly, OEETs operate at very low applied voltages ($< 1\text{ V}$) as they are not limited by the dielectric constant of the insulating layer but by the electrochemical potentials of the semiconductor.

OEETs are typically characterized by measuring the drain current as a function of applied gate voltage for a constant drain voltage. This I-V curve is called a transfer curve or transfer characteristic (Figure 2). It is usually plotted as a semi-log plot, to visualize the large changes of the drain current over several orders of magnitude.

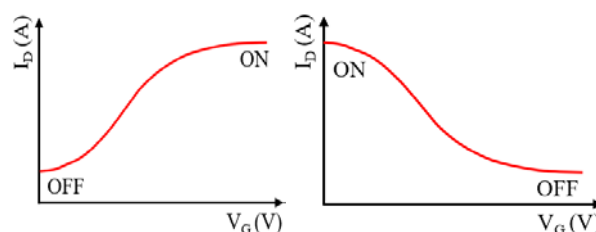


Figure 2. Schematic representation of a transfer curve showing the dependence of the drain current I_D from the gate voltage V_G for a transistor in the accumulation mode (left) and the depletion mode (right)

In the context of transistors as switches one may focus mostly on the so-called on/off ratio, which presents the ratio of the drain current when the transistor channel is fully “on” (meaning the semiconductor is fully doped and thus conductive) and when it is turned “off” (undoped, non-conductive). A large on/off ratio is desired for digital circuits and switches and can be accomplished by a large product of the carrier mobility and volumetric capacitance of the semiconductor. The switching speed of an OEET is usually limited by the velocity of the ions moving through the electrolyte and more importantly the semiconducting layer and is much slower than for conventional transistors. The development of semiconducting polymers that enable both high electronic charge carriers mobilities and high mobility of ions is an active area of research [17].

OEETs can work in two different modes - depletion or accumulation - depending on the semiconductor. Most polymer semiconductors are not doped in their initial state and thus are not conducting. When a gate voltage is applied, and charges are injected (accumulated) in the channel the semiconductor becomes conducting. This is the accumulation mode.

However, the most popular material for OEETs is the mixed conducting polymer PEDOT:PSS (see Figure 3 for molecular structure), where the semiconductor PEDOT is already partially oxidized (p-doped) and the negatively charged sulfonate-groups of the polyelectrolyte PSS provide the stabilizing counter ions. Hence films of PEDOT:PSS are highly conductive without any applied

voltage. PEDOT:PSS is commercially available in different variations and has been used for decades as a printable conducting polymer, which also shows electrochromic properties [18]. Furthermore, the synthesis of PEDOT:PSS has already been shown in a hands-on experiment for teaching [19]. OECTs with PEDOT:PSS operate in the depletion mode. Here, the channel is “on”, when no gate voltage is applied as the PEDOT molecules are in oxidized/ conducting state. Under applied positive gate bias, cations from the electrolyte (e.g., K^+) penetrate the PEDOT:PSS layer and compensate the negative charges of the PSS molecules. Thus, the PEDOT is dedoped (reduced, the hole concentration goes down) and its conductivity and the drain current decrease. The channel is turned “off” (Figure 3). This process is completely reversible and a return to a low gate voltage will restore the channel conductivity. The widespread application of PEDOT:PSS in OECTs relies on its very high carrier mobility, stability in water, easy processing, commercial availability and established biocompatibility [20].

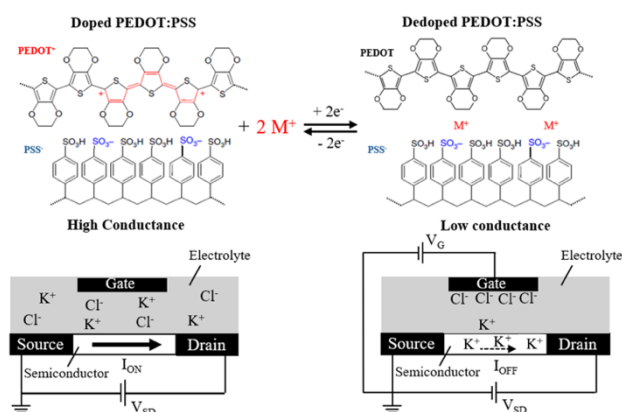


Figure 3. Doping and dedoping of PEDOT in an OECT. Left: Without gate-voltage PEDOT is doped and highly conductive for electrons, which enables a source-drain-current. Right: When a gate voltage is applied, metal cations migrate into the semiconductor and compensate the negative charges of the PSS molecules, resulting in a reduction of the PEDOT molecules (= dedoping) and a decrease in the source-drain-current

3. Original OECT Device

To develop a low-cost hands-on OECT device a collaboration was formed between the department of Chemistry Education at the University of Potsdam (Banerji group) and the Institute of Physical Chemistry at Heidelberg University (Zaumseil group). To follow a thorough methodology, the original OECT device was first built and examined with high-standard scientific methods at the research labs in Heidelberg. In the second step the didactical transformation of the experiment was done in Potsdam according to the aspects “low-risk”, “low-time”, “low-cost”, “low-tech” and “low-waste” [21].

The original experiment was performed by using a OECT structure produced at the Institute for Microsystems, -Actuators, and Systems (IMSAS) from Bremen. It employs a silicon wafer substrate with photolithographically patterned gold electrodes, i.e. a large side-gate electrode and several sets of source/drain electrodes with different channel widths and lengths (Figure 4, left). The

substrate also comprised of several patterned polyimide layers. One layer of the polyimide ensured that the electrodes were only exposed at the edges to the electrolyte, which reduces leakage currents and parasitic capacitances. The second layer enables the removal of spincoated PEDOT:PSS from most of the substrate except in the channel area as it can be peeled off. This patterning step reduces the amount of PEDOT:PSS that must be dedoped and enables detailed and reproducible characterization of the properties of such OECTs [22,23].

PEDOT:PSS from Sigma Aldrich (1.3 w% dispersion in water) with a conductivity of 1 S/cm was used as the conducting layer. By adding ethylene glycol with a ratio of 1:4, it was possible to reach conductivities of up to 621 S/cm [24]. Additionally, 0.6 mL of isopropyl alcohol was added to 1.5 mL of the PEDOT:PSS-ethylene glycol solution to reduce the surface tension for the spin-coating step. Spincoating of 100 μ L of this modified PEDOT:PSS dispersion onto the substrate at 1500 rpm resulted in a layer thickness of about 70 nm. The substrate was subsequently annealed at 120°C for 30 minutes to remove all residual solvents. The top layer of polyimide was peeled off to leave PEDOT:PSS only in the channel area between the electrodes. A drop of 0.5 M NaCl solution in water was applied as the electrolyte, covering the channel as well as the gate electrode (Figure 4, left).

To characterize the transistor, we measured the source-drain current as a function of the applied gate voltage. Therefore, we applied a constant source-drain voltage of 0.6 V and varied the gate voltage between -0.5 V and $+1$ V. The change in current at the drain electrode (I_D) is then measured and plotted against the gate voltage (V_G). The results of that measurement are shown as a transfer curve in Figure 4, right. By applying a negative gate voltage of -0.5 V we measured a drain current of 59 μ A which is described as the ON-State of the device. Increasing the gate voltage leads to a decrease in drain current corresponding to the OFF state of the device. Here the applied gate voltage of 1 V leads to a drain current of 0.16 μ A. The ON/OFF ratio is about 370.

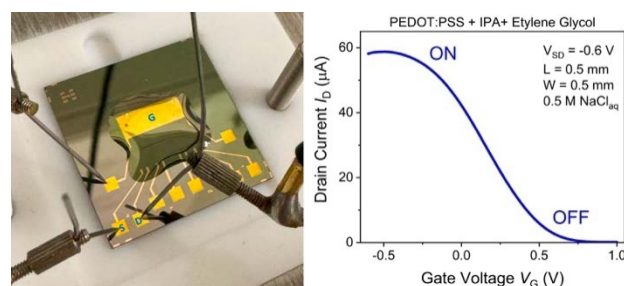


Figure 4. Left: Original OECT with applied electrolyte solution. The electrodes (S: source, D: drain, G: gate) were connected to the semiconductor parameter analyzer via micro-manipulated probe tips. One device contains four pairs of source-drain electrodes (S, D) and one common gate electrode (G). Right: Transfer curve of the original OECT with a channel length and width of 0.5 mm. V_G : gate voltage; I_D : drain current; V_{SD} : source-drain voltage

4. Didactical Transformation

One of the main advantages of OECTs for the demonstration of organic transistors as switches in an

educational setting is the fact that unlike in a field-effect transistor, the gate electrode does not have to be on top of the channel separated by a very thin ($< 1\ \mu\text{m}$) dielectric layer to achieve measurable changes in conductance at low voltages ($< 2\ \text{V}$). The gate electrode can be located quite far away from the channel as long as it is in contact with an electrolyte with mobile ions. This slows down switching from “off” to “on” as the ions have to migrate within the electric field but still takes place within a few seconds. Furthermore, the dimensions of the channel (W and L) can be fairly large (in the mm-range) and do not require special patterning techniques.

4.1. Fabrication of the Hands-on OECT Device

Several didactical adjustments have been made to get a functional OECT device that can be build and examined in a standard school laboratory. In the following, we refer to the OECT, which was originally built in the Heidelberg-labs as “original OECT”, while we refer to the didactically tailored OECT, which was developed in the Potsdam-labs as “hands-on OECT”.

While the original OECT used gold electrodes (applied by thermal deposition), the hands-on OECT uses silver paste which can be easily applied like nail polish with the help of a brush. Since the silver paste is quite easily damaged (i.e. when alligator-clips are connected), the contact area was reinforced with self-adhesive copper tape, which can be easily applied by hand (Figure 5c). To gain a narrow ($\sim 1\ \text{mm}$) and reproducible channel, we first applied a fully closed source-drain-connection with the silver-paste and let it dry. Then, we scratched a small gap into the connection line with the help of a needle pin to create the channel (Figure 5a). Further, we simplified the application of the semiconductor by using drop casting for the hands-on OECT instead of spin coating. For this, we used a small capillary tube and immersed it into the PEDOT:PSS emulsion with the closed side. A tiny droplet adheres to the rod and can be transferred onto the substrate which reduces chemical waste and the need for a cleanup. Also, we reduced the time for annealing the PEDOT:PSS from 30 min to only 5 min. The original OECT used a few drops of electrolyte solution that were applied just before the device was characterized. This was feasible, as the device was held in place by the needle tips of the micropositioners and not moved during the entire measurement (Figure 4, left). To ensure that the hands-on OECT could be easily handled by students during measurement, we introduced a small piece of filter paper soaked with the electrolyte solution. This way the electrolyte was confined but ion-flux was still possible. We replaced NaCl with KCl. This choice is chemically justified by the higher mobility and weaker interaction of K^+ with the PSS^- polyelectrolyte, which facilitates more reversible dedoping of PEDOT and improves switching behavior under low-voltage operation [25]. To enclose the device, we placed another glass slide on top and secured it

with two foldback clips (Figure 5b + 5c).

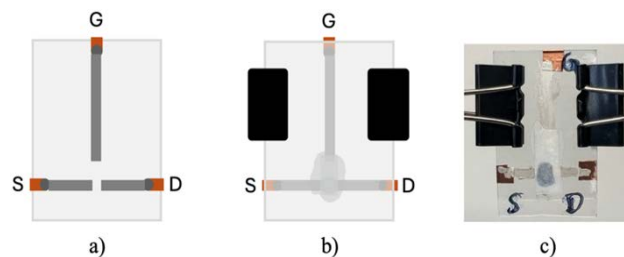


Figure 5. a) Scheme of the hands-on OECT showing the electrode structure with the gap for the channel. b) Scheme of the completely compiled hands-on OECT; c) Photo of the hands-on OECT with electrolyte containing filter paper and the PEDOT:PSS droplet (black spot under the filter paper). Electrode contacts (silver paint and copper foil) are labelled (S: source, D: drain, G: gate)

Furthermore, a visual indicator was required that could be observed by students to conclude that their devices were working properly. As LEDs need more than $1.5\ \text{V}$ to operate, we decided to use the power efficient motor “LE2201” by the company LEMO-SOLAR with an attached propeller. Figure 6 shows how to connect the OECT into the test-circuit along with the propeller-motor, power-source and battery. Scan the QR code or visit our website [26] to watch a video showing the OECT device in operation.

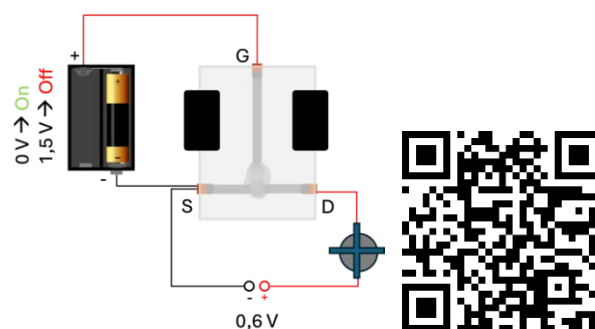


Figure 6. Electrical circuit to test the OECT device. The propeller-motor indicates current-flow between source and drain and thus gives visual feedback to the on/off state of the transistor. Scan the QR code to watch a video or animation of the OECT device

The motor has a threshold voltage of only $0.08\ \text{V}$ with a short circuit current of $6\ \text{mA}$. Since the OECT in the original experiment showed a max. current of only $0.056\ \text{mA}$ we had to find a way to increase the current by a factor of at least 100. Therefore, we changed the applied semiconductor to PEDOT:PSS Clevios™ PH1000 but kept the additives the same. Furthermore, we changed the application method from spin coating to drop casting. By applying a droplet of the PEDOT:PSS we increased the layer thickness of the semiconductor from $70\ \text{nm}$ (spin coating) to about $850\ \text{nm}$. Using channel dimensions of $L = 1\ \text{mm}$ and $W = 2\text{--}3\ \text{mm}$, we were able to measure over $16\ \text{mA}$ in average (Table 1) which was clearly above the threshold for the motor. Some hands-on devices showed even higher ON/OFF ratio than the original OECTs.

Table 1. Data of four hands-on OECTs showing the measured currents for the on state ($I_{\max}$) and the off state ($I_{\min}$) as well as the ON/OFF ratio (rounded to the nearest hundred)

	$I_{\max}$ in mA	$I_{\min}$ in mA	ON/OFF ratio
OECT device 1	22.26	0.04	600
OECT device 2	11.92	0.02	600
OECT device 3	15.74	0.05	300
OECT device 4	14.56	0.04	400
$\emptyset$	16.12	0.04	475

Please visit our website [26] to download the lab-protocols, where we describe in detail how to formulate the PEDOT:PSS solution and how to build the hands-on OECT device along with a risk-assessment for schools.

4.2. Teaching Material – OECT Animation

The elementary processes, which occur when the OECT is triggered between the ON and OFF state are quite complicated to understand - especially for highschool students. To support the learning process, we have compiled an animation using PowerPoint (PPT), which shows the elementary processes within the OECT on the submicroscopic level (Figure 7). Please note: As highschool students are not familiar with the concept of holes as a quasi-particle, the current-flow in the PEDOT layer is depicted as an electron movement instead of a hole-movement. You can access the animation free of cost (cc-licensed) from our website [26] (or scan the QR code in Figure 6).

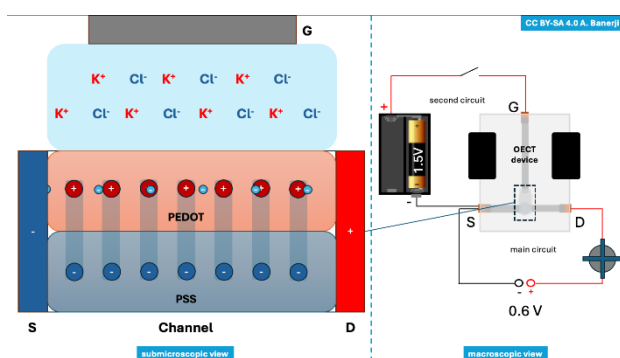


Figure 7. Screenshot of the animation showing the macroscopic and submicroscopic view of the elementary processes in the hands-on OECT device. Scan the QR Code in Fig. 6 to access the animation free of cost

4.3. Learning Objectives

In designing the hands-on OECT experiment, we defined explicit conceptual, experimental, and epistemic learning objectives to align the activity with current educational frameworks.

Conceptual learning objectives:

- Students explain the basic structure and operating principle of an organic electrochemical transistor.
- Students describe the role of ions and electrochemical doping in modulating the conductivity of PEDOT:PSS.

- Students differentiate OECTs from conventional field-effect transistors in terms of switching mechanism and materials.

Experimental learning objectives:

- Students fabricate a functional OECT using low-cost materials and handle conductive polymers (PEDOT:PSS) safely.
- Students measure transfer characteristics (I_D - V_G) and determine the ON/OFF ratio of their device.
- Students relate experimental observations to changes in doping state and ionic motion within the channel.

Epistemic learning objectives:

- Students experience how research topics can be transformed into accessible school experiments (“curricular innovation”).
- Students evaluate measurement data critically (e.g., reproducibility, sources of error).
- Students reflect on the role of simplified models in understanding modern electronic devices.

5. Testing the Experiment with Students

To investigate the reliability of the hands-on OECT and to identify further optimization potentials, we carried out a small pilot-study along with eight students from grade 12 at a highschool in Berlin (Germany). To monitor the learning outcome, the study was designed as an intervention with a pre-post knowledge-test. As an introduction the students heard a short lecture about the relevance of bio-organic electronics and the functional principle of a transistor as an “electronic switch”. After the lecture the experimental phase followed. For this, we prepared five workspaces equipped with all necessary materials to build the hands-on OECT device along with printouts of the lab-protocol for each student. Six students worked in pairs, while two students worked alone. Two tutors were available during the whole course for any questions and assistance. After finishing the experiment, the functional principle of the OECT was explained using the PPT-animation. In the next phase, the students could take a short break, followed by the post knowledge-test and a closing-session, where general feedback was collected and the workspaces were cleaned. The overall time of the pilot-study was about two hours (Table 2).

Table 2. Structure and schedule of the OECT intervention program

Time	Contents/ Activities
13:45-14:05h	Welcome & pre-knowledge-test
14:05-14:15h	Short introduction lecture on transistors and OECT
14:15-15:05h	Experiment: Construction of the hands-on OECT
15:05-15:10h	Animation of the functional principle of the OECT
15:10-15:15h	Short break
15:15-15:30h	Post knowledge-test
15:30-15:45h	Feedback, Cleaning & Closing

5.1. Results of the Experimental Phase

The students conducted the experiment mostly self-independent using the lab-protocol (Figure 8). At two steps of the experiment students needed help from the tutors:

1. The lab-protocol did not specify the amount of KCl-solution, which needed to be applied onto the small piece of filter-paper.
2. The students had difficulties to build the electronic circuit (which was needed to test the OECT) from the sketch provided on the lab-protocol. The circuit was quite complex as two different power-sources and a small fan (which indicated the on/off-state) had to be connected to the OECT device.

The problems were not severe and could be solved quickly with help of the tutors. All other experimental steps did not seem to be challenging for the students. All five groups could achieve a working OECT device, which was able to drive the fan in the on-state and switched it off, when the gate-voltage was applied and triggered the off-state of the OECT. The experiment turned out to be quite robust as some students worked less accurately and nevertheless could succeed in the experiment.

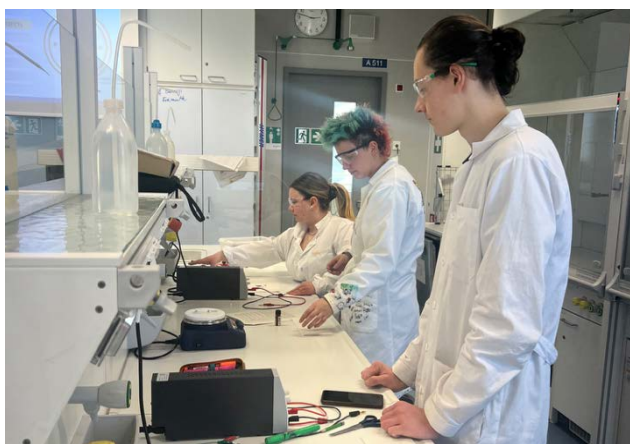


Figure 8. Students conducting the experiment for building the hands-on OECT device. Photo-credit: A. Banerji

5.2. Results of the pre/post knowledge-test

The knowledge-test was conducted anonymously and contained the following five questions:

1. Give examples for applications, where transistors are mainly used.
2. Give examples for semiconductors, which are used in transistors.
3. State at least one advantage of OECT compared to conventional transistors.
4. Describe in own words the structure of a) a conventional transistor and b) an OECT. (Alternatively, you can also draw a sketch)
5. Describe the functional principle of a transistor.

The questions were the same for the pre- and post-test. For evaluation, each answer was rated between 0 and 3 (0: incorrect; 1: partially correct; 2: mainly correct; 3: fully correct). The maximum of points was therefore 15. For statistical display the sum of all collected points was built,

and the percentage of correct answers was calculated for each student (Figure 9).

Figure 9 shows that the students had only very little pre-knowledge about transistors and semiconductors and their applications. After the intervention all students reached a minimum of 65% of correct answers, which underlines that the course triggered learning outcomes about the topics mentioned above.

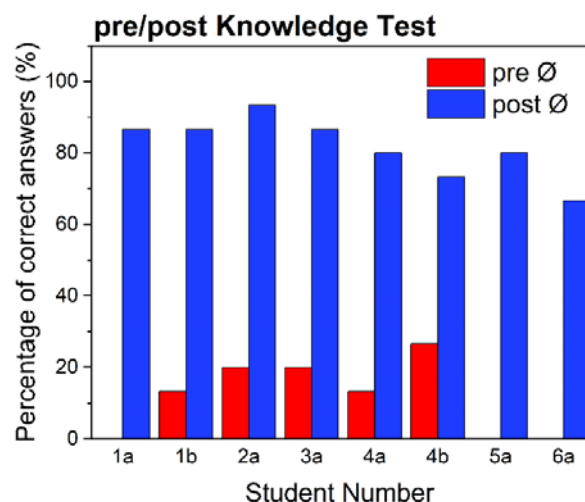


Figure 9. Results of the pre/post knowledge-test showing the percentage of correct answers per student (number = student-group, small letter = individual student)

5.3. Feedback of the Students

At the end of the course general feedback was collected via a google-form (not shown here). The students showed great interest in the medical applications of OECTs and liked the hands-on experiment as it was not too challenging and gained lots of fun. Only a few students mentioned that the application of KCl-solution and the construction of the circuit was quite challenging. Consequently, we revised the lab-protocol by adding detailed information on how to apply the solution and how to build the circuit. All students complimented the OECT-animation and evaluated it to be very clear, vivid and thus suitable for illustration. The students rated the lab-course overall with the German grade 1,1 (equals to an “A” in USA).

6. Conclusion and Outlook

We have shown that transistors are not a “closed book” anymore. With the presented hands-on OECT it is possible to teach transistors along with a modern context and a reliable experiment. The hands-on OECT experiment currently serves as a solid prototype for further developments and integration into curricula. Ongoing efforts will improve the device based on the low criteria. We want to explore different semiconductor materials, potentially enabling operation in accumulation mode. Also, we want to investigate different electrolyte-solutions as their influence on the OECT is not yet fully understood and therefore still an object of current research [25]. For

curricular integration, we aim to develop an experimental kit, which will complete our existing kits on organic LEDs and organic solar cells [27]. Furthermore, we want to combine two or more OECT devices to construct so called logic gates. These are fundamental electrical components, which are used to realise Booleans functions (e.g. AND, OR, NAND etc.). Several logical gates can form so-called flipflops, latches or multiplexer, which are the basic components of microprocessors.

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