Insect Olfaction as a Natural Blueprint of Gas Sensors?

Bernhard Weißbecker and Stefan Schütz

Abstract Biologically inspired sensory solutions utilize highly developed organs of perception that are evolutionary tuned towards compounds correlated to ecological functions. After millions of years of "survival of the fittest" insects, e.g., are trained to detect specific compounds that serve reliably as cues to find hosts and mating partners, or to avoid enemies and competitors. The multitude of insect species (>1,000,000) and their ecological interactions provide a vast range of possible biosensors based on natural sensory systems. Also biomimetic approaches can lead to various applications for tracking and monitoring of chemical compounds in environmental and industrial processes. Biosensors utilize organic components (e.g., proteins, cells, tissues, or organisms) within a technical appliance. The combination of technical devices with biological sensory units provides detectors which are superior to mere technical solutions in selectivity and sensitivity. For instance, by integrating insect antennae in the gate of a field-effect transistor (BioFET), volatile trace compounds are directly detectable in the ppb range. The complex biochemical detection system in the antenna of the insect serves as a selective detector for compounds that provide vital information about its environment. Thus, knowing the selectivity and sensitivity pattern enables us to design biomimetic semiconductor sensors utilizing the evolutionary experience of insects in combination with reliability and ruggedness of technical semiconductor gas sensors for highly specific gas-sensing tasks.

Keywords Biomimetic sensor, Biosensor, Electroantennography, Insect olfaction, Semiconductor gas sensor, Smoke detection, Volatile organic compounds

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1 The Key: Observation of Insect Behavior

1.1 Introduction to Insect Behavior

Simply observing animals in nature is often a complex task. Natural behaviors are typically complex composites of distinct subroutines. Differentiating among the behaviors and determining which stimuli elicit which behavior is in many cases challenging. Insects, however, in spite of their minute size, display a wide span of behaviors. Most of them are stereotype and executed in an obligate manner on the presentation of the adequate stimulus. Even a small creature like the honeybee shows a behavioral repertoire of about 60 distinct and recognizable behaviors [1]. Additionally, insects comprise a highly diverse group of organisms and have proven particularly rewarding models in studying olfaction. Insects decode their chemical environment, the peripheral olfactory system adapts evolutionary, and in turn mirrors the adaptive forces acting on the system over evolutionary time [2].

Insects show complex behaviors that are composed of behavior components which are elicited, maintained, or terminated by environmental (external), interindividual (external), and intraindividual (internal) stimuli. Appetitive behavior is such a behavior component that is governing search for vital resources like food, mating partners, and sites for laying eggs.

Most of the time, appetitive behavior is guided by sensors measuring different sensory modalities as olfaction, vision, humidity, temperature, tactile, and gustatory senses. This warrants a multimodal sensory integration [3]. However, in this contribution, we focus on the olfactory sense which is closest related to the tasks of gas sensors. From cybernetic point of view, an appetitive controller for food finding is composed of three main subsystems: chemotaxis, feeding arousal, and integrating behavior controls [4]. Chemotaxis is an innate behavioral response by an organism to an external directional gradient of stimulus intensity, that is, a response to a chemical concentration gradient. Insects use their antennae to detect

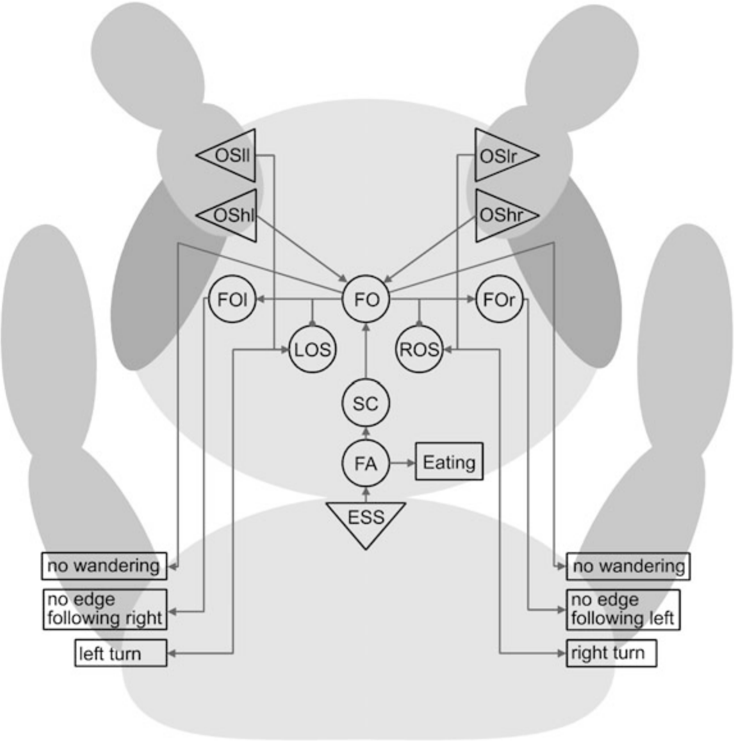

Fig. 1 Cybernetic layout for an appetitive controller. *OSlr* odor sensor low right, *OShr* odor sensor high right, *FO* following odor, *FOl* following odor left, *LOS* left odor strength, *SC* search command, *FA* feeding arousal, *ESS* energy status sensor (from www.mindcreators.com/AppetitiveController.htm, simplified)

quality, quantity, and gradient direction of volatile chemical compounds. Inducers of locomotion towards increasing steps of concentrations are considered as attractants, while repellents result in moving away from the source. Feeding arousal can briefly be described as “hunger” being an important internal subsystem relating current demand of the organism to movement behavior. The final behavior of an insect depends on many internal and external variables, and hunger is one of the most important internal ones. Next, different behaviors are mutually exclusive. Performing random wandering for untargeted exploration of the environment at the same time with targeted movement towards a close food source are not compatible behaviors. Even edge-following behavior which is important to go around possible obstacles between insect and odor source has to be modulated appropriately in order to reach the odor source. Behavior integration neurons provide control when one behavior is active or not (Fig. 1).

Before the insect can feed, it must first be able to find food. The purpose of the chemotaxis control neurons is to orient the insect so that it moves towards a food source it can smell. Thus, the antennal odor sensor neurons are critical for chemotaxis. In our cybernetic model, these neurons are the odor sensor neuron low left (OSll), odor sensor neuron low right (OSlr), the odor sensor neuron high left (OShl), and the odor sensor neuron high right (OShr). The low and high in the odor sensor names refers to the gain which controls the sensitivity of that antenna. An odor sensor with a very high gain will be able to detect smaller quantities of volatile compounds and will thus be able to detect food at a much longer distance (long-range orientation). However, since it has such a high gain, it also means that as it gets closer to the food, the high gain sensors will saturate and the animal will no longer be able to get any useful orientation information from them. Low gain sensors will not be able to detect food unless they are very near to it. But it also means that they will be able to guide the insect even when they are close to immediate contact with the food (close range orientation). The outputs from these odor sensor neurons are fed into left odor strength (LOS) and right odor strength (ROS) neurons. Odor sensors from the left side excite the LOS neurons and inhibit the ROS neurons, and chemical sensors from the right side excite the ROS neurons and inhibit the LOS neurons. This performs a comparison of the odor strength values that are coming from left and right side that can be used to determine which way to turn in order to orient the insect towards the food.

This simplified model example of insect food-finding behavior displays the impact of properties of the antennal odor sensors on behavioral outcome. In turn, observation of insect behavior, especially attraction towards specific odor sources, can provide valuable clues for sophisticated sensor properties.

1.2 Example **M. acuminata, M. atrata***: Long-Range Orientation to Forest Fires*

Already at the beginning of the twentieth century, firemen reported on black beetles that flew in masses towards burning forests, hampering efforts to extinguish fires, and even attacking firemen [5]. Reports on this unusual pyrophilic ("fire-loving") behavior of the black jewel beetle *Melanophila acuminata* included speculation that the beetle might be able to orientate towards a forest fire through olfactory means [6].

Pyrophilic beetles depend on forest fires for their reproduction. The adult beetles are living inconspicuously in forests with high dead wood content mostly with a predatory lifestyle. At high temperatures and low air humidity, they show an increased flight and searching behavior. Once picking up volatile organic compounds characteristic for forest fires, such insects approach ongoing fires and invade the burnt area immediately after fire. For long-range orientation towards a fire, these insects have special sensors for smoke [7] and infrared radiation [8]. Whereas the olfactory receptors for smoke are located on the antennae, the infrared receptors are housed in sensory organs, which can be found on the thorax or on the abdomen. Two genera of jewel beetles (Buprestidae) can be classified as

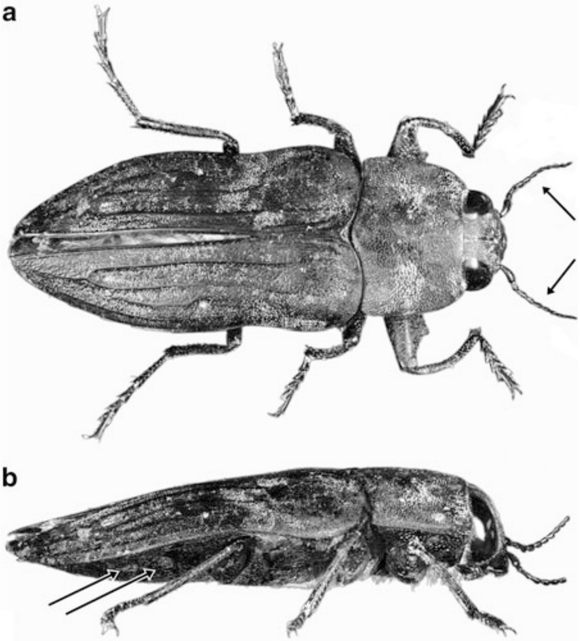

Fig. 2 One example for pyrophilic jewel beetles. The black fire beetle (*Merimna atrata*) occurring in Australia. (**a**) *Top view* antennae marked with arrows, (**b**) *side view* infrared receptors marked with arrows

pyrophilous: more than ten species of the *Melanophila* genus, which are distributed nearly all over the northern hemisphere, and the buprestid beetle *Merimna atrata* (Fig. 2), which is endemic to Australia [9]. Despite the fact that there is some debate about how these beetles are able to approach forest fires over distances of more than 30 km [10, 11], measurements with a biosensor on the basis of intact insect antennae of *M. acuminata* showed significant responses to wood smoke of a 5 m^3 heap of burning wood logs in more than 2 km distance [12], and analogous measurements with intact insect antennae of *M. atrata* showed significant responses to wood smoke of a 15 ha eucalypt forest fire in more than 20 km distance, suggesting a key role of olfaction in long-range attraction to forest fires.

Despite the fact that *Melanophila* and *Merimna* show a similar behavior and belong to the same family of jewel beetles, their infrared receptors are totally different from each other, suggesting that this specialization to fire developed independently in both genera from the northern hemisphere and from Australia [11].

1.3 Example **M. acuminata, M. atrata***: Close-Range Orientation on Burnt Forest Sites*

Arriving on the freshly burnt area, the males of both genera often stay close to burning or smoldering wood looking for females of their species, which are attracted to the fire, too. Infrared receptors might serve here for detecting sites that are not too hot to alight [13]. After mating, the females deposit eggs under the bark of the freshly burnt trees. Only there, the wood-boring larvae of *Melanophila* and *Merimna* can develop by feeding in the weakened and preheated wood of fire damaged trees [14]. Consequently, fire detection is the compulsory precondition for the survival of all these pyrophilous insect species. They are not only able to detect fires from big distances, moreover, they are able to discriminate trees that are charred to the core from trees that still contain preheated, but uncharred wood as substrate for their larvae. Egg deposition behavior was observed exclusively on trees with an uncharred wood core. Consequently, the young larvae started to feed in the transition region between charred and unaffected wood, providing preheated wood with partially depolymerized cellulosis which is easier to digest like in a natural cooking pot. This kind of information is not retrievable by vision or infrared detection but only by the detection of volatile organic compounds specifically generated by early stages of thermal decomposition of wood leaving the charred trunk through thermal shrinking fissures in the wood.

2 The First Step: Analysis of Olfaction by Trace Analysis and Electrophysiology

2.1 Trace Analysis of Smoke Volatiles

In order to analyze traces of airborne volatile compounds, air has to be sampled in a reproducible manner. If the volatile target compounds have a boiling point well below ambient temperature, like permanent gases, they can be sampled in a defined enclosure, like a glass flask or syringe, as a gas sample. If the volatile target compounds have a boiling point within the range or above ambient temperature, direct gas samples will be depleted by adsorption to the walls of the enclosure. Therefore, most volatile organic compounds have to be sampled on an absorbent and have to be desorbed prior to analysis by a gas chromatograph (GC). Moreover, volatile compounds are often present only in high dilutions so that most of the time a pre-concentration is necessary. Most sampling methods use an active sampling approach, sucking a defined volume of air into an enclosure or over an absorbent serving as a trap. Common absorption materials provide a huge internal surface like charcoal or the polymer Tenax® [15]. When sampling smoke volatiles, aerosol particles have to be taken into account. They are prone to distort sampling results and have to be kept out of the volatile samples by special particle filters [16]. Another way to circumvent distortions by airborne particulate matter is to use passive sampling techniques like solid phase microextraction (SPME) suffering the disadvantage of an ill-defined sample volume [17].

The most widespread set-up to analyze volatile organic compound samples is a gas chromatograph coupled to a detector unit allowing to identify and to quantify the separated compounds in a mixture of volatiles. First, the volatile sample has to be transferred into the GC by an injector. In case of direct gas sample, injection or direct headspace techniques [18] can be applied. In case of compounds trapped on an adsorbent, the sample has to be eluted by a solvent (chemodesorption) or evaporated into an inert gas flow by elevated temperatures (thermo-desorption) [17]. After injection the compounds are moved by the inert carrier gas through the GC column. Interactions with the column coating determine which compound is retained longer or which compound is eluting earlier. The retention time of a specific compound depends on geometry and chemistry of the column, carrier gas and carrier gas flow, temperature during the separation, and the identity of the compound. Identification of a compound by retention time requires a separation of aliquots of the sample on at least two different columns. Having passed the column, the compounds can be detected by different detectors like the flame ionization detector (GC-FID) essentially detecting every compound that is combustible in a hydrogen-oxygen flame or like the mass spectrometric detector (GC-MS) that allows structural elucidation of the eluting compounds [19].

2.2 Electroantennographic Analysis of Volatiles

The biochemical transduction pathway in insect olfaction generates membrane depolarizations in olfactory neurons which can be detected as a summed electroantennographic response of the insect antenna. Although intensive research has been conducted on understanding the biochemical interactions involved in insect olfaction, the interactions are not as yet fully understood. Thus, we shortly summarize the current state of knowledge: once an odor plume reaches the airspace around an insect, it enters nanopores in the cuticle of an olfactory sensillum. The cuticle covers the antenna in order to prevent mechanical damage and desiccation of the sensory neurons housed in the sensillum. These wax-filled nanopores allow volatile organic compounds to diffuse into the sensillum lymph that surrounds the neurons inside the sensillum. This kind of enriching unpolar volatiles in cuticular wax provides a pre-concentration of the volatiles enabling insect antennae to perceive volatiles reliably in air and in water. So-called odorant-binding proteins (OBPs), first discovered by Vogt and Riddiford as pheromone-binding proteins (PBPs) [20], selectively bind and transport the mostly hydrophobic odor compounds through the hydrophilic sensillum lymph to the olfactory receptor contained in the neuronal membrane (Fig. 3).

It is proposed that due to the three-dimensional tertiary structure of these monochain proteins, a binding cavity is formed in which functional groups of amino acids are exposed to interact with the peculiar structure and charge distribution of the odor molecule [21]. The lipophilic odor forms a complex with the OBP and can diffuse through the aqueous sensillum lymph towards the dendrite membrane. In the dendrite membrane, the odorant receptor (OR) can form a spatial functional unit with an ion channel [22]. Upon contact of this OR-ion-channel unit with the OBP-odor complex, the ion channel opens allowing an influx of potassium ions into the olfactory neuron causing a dose-dependent depolarization of the olfactory

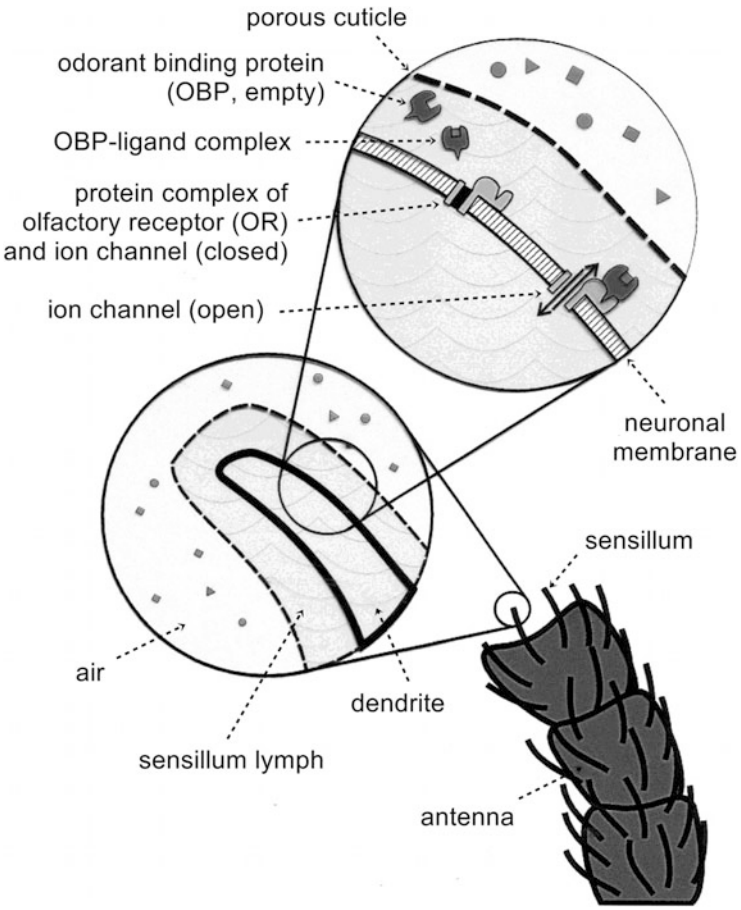

Fig. 3 The functional concept of insect olfaction: odorant receptor proteins (OR) linked to ion channels are embedded in the neuronal membrane of a dendrite inside a sensillum on the antenna. Contact with a complex formed by an odorant-binding protein (OBP) and an odor ligand triggers ion influx, thus causing depolarization of the olfactory neuron, modified from [12]

neuron. A summation of these depolarizations over the antenna can be recorded as EAG signal (Fig. 4). When the odor is present in a detectable concentration, a sufficient number of cascades give rise to membrane depolarizations in different dendrites of one neuron summing up to exceed the neuronal activation threshold. This will lead to an action potential from the sensory neuron which is transferred into the insect central nervous system, where it is further processed into odor perception [23]. Thus, peripheral olfactory transduction is the basis for the sensitivity and selectivity of odor perception, both of single odorant compounds and of odorant mixtures [24].

As the adaptation of the olfactory sense in insects to the distinctive demands for the single species has gone through millions of years of selection of the fittest, the

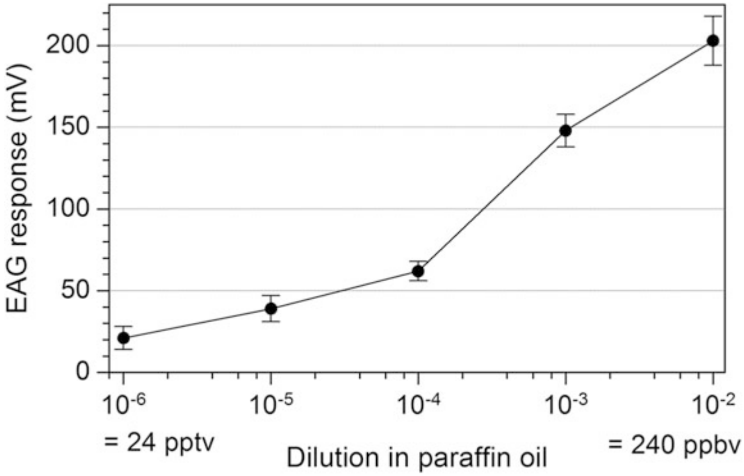

Fig. 4 Dose-response curve of an antenna of *Melanophila acuminata* to guaiacol. The odor dilutions are provided by air in equilibrium with solutions of the odor compound in paraffin oil in decadic dilution steps. The vapor pressure of guaiacol is modified by diluting the compound in paraffin oil according to Henry's law yielding the outlined equilibrium concentrations of guaiacol in air. The EAG response of the antenna exposed to a 0.5 s stimulus of odor laden air is amplified by a factor of 100

resulting compounds can be regarded as marker compounds in the ecological interaction between the insect and its environment. A combination of trace analysis, like gas chromatography mass spectrometry with a parallel electroantennographic detection based on insect antennae resulting in one GC-MS/EAD setup [25], allows the identification of single compounds that are selectively traceable by an insect via scent (setup see Fig. 5, example chromatogram see Fig. 6).

If compounds released by burning pine wood are collected by a charcoal trap, chemodesorbed from the trap by a solvent and injected into the GC-MS/EAD setup, the complex mix of thermal decomposition compounds is separated by the gas chromatographic column and guided in parallel to the mass spectrometer and an EAG equipped with the antenna of *M. acuminata*. Peak formation in the EAG trace marks out compounds that are detected by the insect. Simultaneous peak formation allows the identification of electrophysiologically active compounds by mass spectrometric analysis.

The beetle antenna shows a high sensitivity to different terpenes. *M. acuminata* is able to use them as marker compounds for coniferous trees, the preferred host tree of the beetle. Moreover, the beetle antenna shows a high sensitivity to guaiacol derivatives emerging from the pyrolysis of wood lignin. This enables the beetle to differentiate between grass fires only burning the herbal layer and full forest fires. Only the latter will provide sufficiently damaged trees for its offspring. The relation of guaiacol and substituted guaiacols allows the beetle to assess the fraction of smoldering wood logs and, thus, potential space for egg deposition. Compounds released by forest fires and detected by the antenna of its Australian relative,

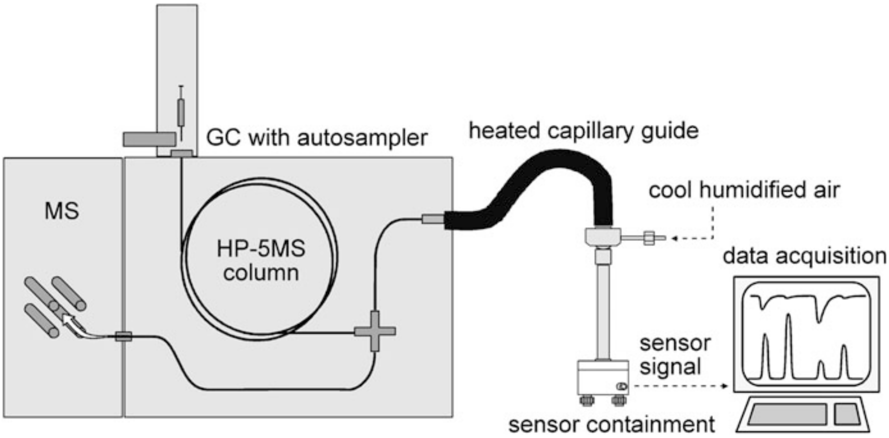

Fig. 5 Schematic of a gas chromatograph coupled in parallel to a mass spectrometer and an electroantennographic detector (GC-MS/EAD), modified from [24]

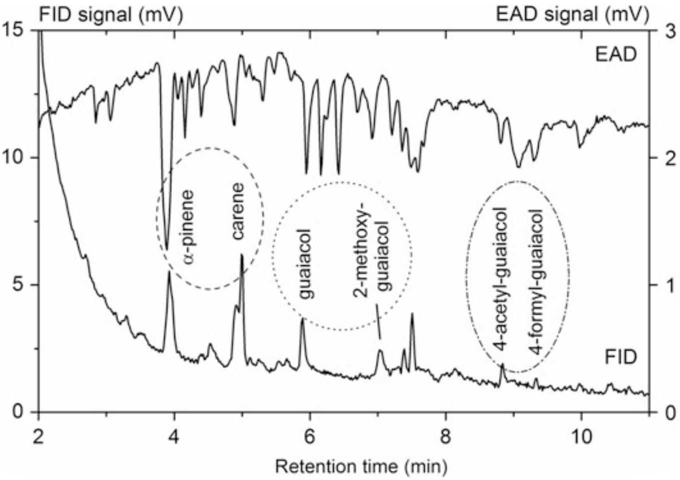

Fig. 6 Result of combined gas chromatography/flame ionization detection (GC-FID/EAD) utilizing the antenna of *Melanophila acuminata*. Simultaneous peak formation allows the identification of electrophysiologically active compounds, in this case guaiacol derivatives and terpene compounds. The differently dashed circles designate different groups of bioactive volatile compounds: marker compounds for wood species burning, marker compounds for burning wood, marker compounds for smoldering wood, modified from [7].

M. atrata can be grouped in the same way, and again, the guaiacol derivatives are used as marker compounds for attractive full forest fires. The utilization of the same kind of marker compounds despite separate development suggests that the guaiacol compounds might provide a robust set of marker compounds for wood smoke detection.

The striking performance of insect olfaction in distinctively responding to ecologically relevant compounds has been verified by many studies [26–29] and can inspire a wide range of biosensor applications. As insect species appear in most ecosystems all over the world and are adapted to many, often very distinct olfaction-based interactions with their environment, the amount of potentially usable marker compounds for biosensors based on insect olfaction is extremely large. The applicability of these marker compounds for economic purposes implies that biodiversity of insects can provide a considerable storehouse of evolutionary improved sensor designs.

3 The Second Step: Utilization of Insect Antennae as Biosensors

3.1 Introduction to Biosensors

One of the main drawbacks of conventional analytical tools is that most of them are not suitable for online measurements during field analysis. These methods are highly sensitive, accurate, and provide reproducible values with suitable detection limits. Nonetheless, they are expensive, large in size, require highly skilled personnel to operate, and are not rugged for field measurements. Therefore, the quest for designing sensitive and selective sensors [30] has now become a major topic in modern research. Miniaturization [31] is important in order to make them suitable for online applications [32]. Biosensors promise to meet this need for small online measuring devices.

Basically, a biosensor is a measuring device that traces chemical compounds, organisms, or physical quantities by spatially and functionally combining a biological component with a physical or chemical transducer [33, 34]. This definition suggests a wide field of possible applications, as it neither refers to any peculiar biological components nor does it describe any concrete physical quantities. Actually, the field of possible realizations of biosensor concepts is quite extensive.

The integrated biological component could, for instance, be an organic molecule, like an enzyme or an antibody. These biochemical structures perform distinctive tasks in organisms and therefore interact with only a selected number of other chemical compounds that occur sometimes only in low concentrations. This selectivity can be utilized in a sensor concept that responds selectively and sensitively towards distinct compounds. The biocomponent can also be an organelle, cell, organ, or a complete organism (Fig. 7).

As a technological part of the sensor, a transducer is defined by its function and not by its mode of operation. Its task is to convert the specific biological/chemical

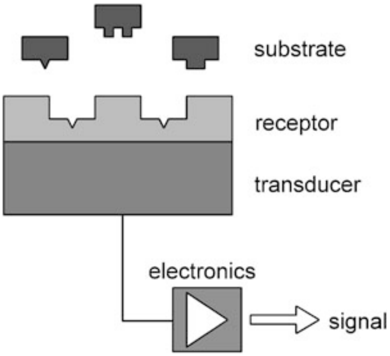

Fig. 7 Functional principle of a biosensor (simplified), modified from [12]

interaction of the biocomponent and an analyte into a physical/chemical response with a measurable output, generally electrical signals. One of the first applications of a biosensor published was a system to measure the concentration of glucose in blood [35]. Here, the enzyme glucose oxidase was immobilized with a dialysis membrane on a platinum electrode. The enzyme metabolizes glucose to gluconolactone while the produced hydrogen is transformed to hydrogen peroxide under consumption of oxygen. Hydrogen peroxide is detected by an amperometric electrode. Alternatively, the consumption of oxygen can be recorded. The biocomponent is in this case the dissolved glucose oxidase and the transducer a platinum oxygen electrode. A permeable membrane keeps the solution around the electrode.

Biosensors can be classified by the type of the used biocomponent, the stage of development (generation), or the type of transducer.

Enzymes (enzyme sensors) and antibodies (immunosensors) are utilized as biocomponents in biosensors where the substrate is detected by docking on a selective protein. One can differentiate between catalytic sensors and affinity sensors depending on whether the formation of a protein/substrate complex yields a metabolic product or not. A microbial sensor utilizes living cells, for instance, coupled to an oxygen electrode that measures respiration processes of the cell by means of the oxygen uptake. This utilization of living cells or tissue opens new perspectives for biosensor applications. However, it also presents a technical challenge to cultivate functional cells on a transducer and to obtain a sufficient storage protocol for the biosensor [36]. Moreover, biological receptors like complete sensing organs, for instance, insect antennae can be used taking advantage of the biological integration of biological receptor and biophysical transduction unit, leaving only the electronic part to the technological side.

The above mentioned glucose sensor of Clark and Lyons uses a membrane in order to immobilize enzymes on an electrode. This setup is also designated as a biosensor of the first generation [33]. Enhancements to this technique are sensors where the biochemical receptors are directly bound to the surface of the transducer (second generation) or immobilized directly on an electronic control device, for instance a transistor (third generation). In particular, field-effect transistors

(FETs) are convenient because of their high input impedance. The combination of a FET with a biocomponent, for instance an insect antenna, is referred to as a BioFET [37, 38].

The most important types of transducers are electrochemical, optical, mass sensitive, or thermal sensors [39]. An example of electrochemical transduction is the amperometric detection especially used for catalytic enzyme reactions. Optical sensors can utilize the absorption, fluorescence, or bioluminescence of molecules and organisms as input.

One technical realization of mass sensitive sensors is the piezoelectric sensor by modifying the surface of a quartz oscillator with an enzyme or antibody. When biocomponents from the surroundings attach to its surface, the total mass of the crystal changes, and due to the Sauerbrey equation, the oscillating frequency of the quartz also changes. Thermal sensors detect the production or consumption of heat during biochemical reactions.

Conventional methods of instrumental chemical analysis, especially GC-MS, require high laboratory costs. In this context, biosensors offer approaches for improved methods that allow real-time on-site analytics [40].

To detect, for instance, a fire marker compound in the woodland, standard methods require sample collection of several hours from ambient air. GC-MS analysis is then performed with a throughput of 20 samples maximum per day. Therefore, the manual labor for sample preparation and the operation of the instrumental setup is very cost intensive, restricting these conventional methods to the survey of a limited number of samples.

A portable measuring device without extensive sample preparation is needed to establish convenient applications for practical on-site use [39]. A biosensor with an appropriate selectivity can detect compounds directly in their matrix without pre-concentration or purification. This will inter alia enable the recording of data in a high spatial and temporal resolution in order to follow a concentration gradient and thereby, localize the source of smoke. However, biosensors provide less accurate quantification of compounds in comparison with conventional techniques of trace analysis.

3.2 A Biosensor on the Basis of Insect Antennae

The basic idea of a biosensor based on insect olfaction is to utilize the extremely high sensitivity and selectivity of olfactory receptors. The silk moth *Bombyx mori*, for example, is able to trace 1,000 molecules per second of the pheromone bombykol in one cubic centimeter of air [41]. This is equivalent to a 1-g sugar lump diluted within and distributed over the whole water volume of Lake Constance (Bodensee). However, this sensitivity is unrivalled yet and can’t be mimicked by technological gas sensors. Moreover, insect antennae display an evolutionary adaption of insect olfaction to the detection of marker compounds even in complex environmental conditions.

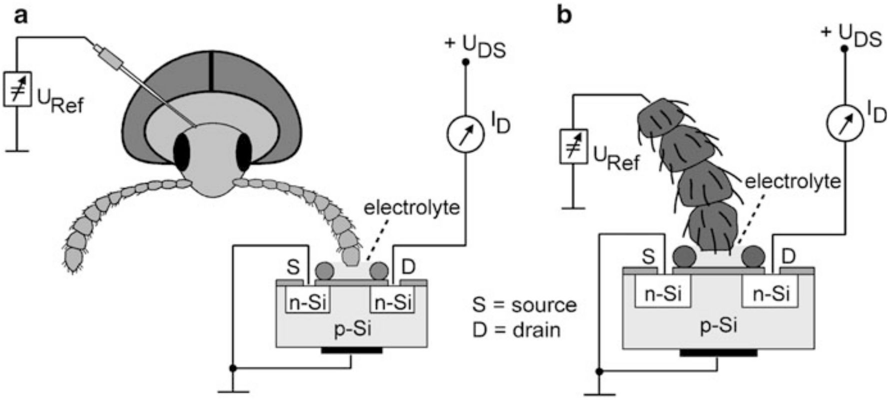

Fig. 8 BioFET hybrid consisting of an insect antenna and a field-effect transistor (FET) with intact pyrophilic beetle (**a**) and isolated antenna setup (**b**), respectively

The black jewel beetle *M. acuminata* can, for instance, detect the burnt scent of a single charred tree over a distance of several kilometers [7]. This striking performance is based on the extremely high sensitivity of the antenna of this insect for guaiacol compounds, reliably detecting guaiacol down to the low pptv (parts per trillion in volume) range (Fig. 4). Therefore, the combination of a highly specialized biochemically operating insect organ with a signal amplifying and processing electronic device can lead to a highly sensitive detection of organic trace compounds combined with a high time resolution in the atmosphere.

The utilization of an intact insect antenna as a biocomponent requires a mechanically and electrically stable junction while avoiding damage to the organ. Electrical and mechanical features of this hybrid device of an insect antenna joint to a field-effect transistor (Fig. 8) rendered this BioFET as particularly reliable [42, 43]. In the case of the "whole-beetle" setup, the antenna of a beetle was directly coupled to the gate of the FET via an electrolyte solution, whereas for the "isolated antenna" setup, it was removed from the beetle. The biochemical cascade inside the antenna finally leads to the formation of an electrical potential drop across the receptor's cell membrane and thus, to a dipole potential over the whole antenna. The latter modulates the conductance of the FET channel between source and drain, inducing a distinct variation of the drain current I_D, which is dependent on the particular odor concentration [44].

The immanent miniaturization of the insect antenna as well as the miniaturization of the microelectronic part allows manufacture of biosensor circuits of the size of a 1C coin. Such sensor heads are deployable in portable biosensor systems to enable high-resolution data acquisition in situ. As distinctive example an application of biosensors on the basis of insect antennae in smoke detection is described below.

The first possible application that comes into mind is to use the biosensor for the same purpose as the beetles themselves, i.e., detecting forest fires. As laboratory and field experiments revealed, a biosensor on the basis of antennae of *M. acuminata* can detect a fire comprising of only a single tree over a 2-km distance and can be traced by the concentration gradient of smoke components and wind direction through a dense forest stand. Combining the high sensitivity and selectivity for marker compounds of fire with an identification of the kind of fire and the traceability of the source, a biosensor based on the antenna of *M. acuminata* can be a powerful on-site tool to be used as the first link in the fire-fighting chain.

Considering further possible applications of this kind of biosensor, it is important to keep in mind that it detects smoke components such as guaiacol compounds very sensitively and that these compounds originate from the pyrolysis of lignin, one of the basic constituents of wood. However, fossil wood (i.e., coal) contains lignin, too. Thus, combustion products of fossil wood (i.e., coal) can also be detected by the biosensor.

Combustion products of diesel fuel or gasoline do not elicit comparable signals.

This enables the design of a biosensor based on the antenna of *M. acuminata* to differentiate between compounds released by dangerous smoldering fires in coal storage units and frequently occurring background compounds, for example, originating from gasoline or diesel combustion engines. Thus, false alarms caused by engine exhausts can be avoided and a reliable fire tracking system could be based on the performance of the biosensor. However, the limited lifetime of the insect antennae poses a serious obstacle for the design of monitoring systems on the basis of this kind of biosensor. This kind of biosensor is most suitable for on-site applications like high sensitivity detection and track following nicely complementing classical analysis systems.

3.3 Biomimetic Approaches to Sensors on the Basis of Insect Olfaction

Evolutionary processes like selection with respect to efficiency of resource location force the development of highly reliable markers for specific resources. Especially challenging is the inherent high variability of natural sources mostly consisting of entities that do not want to be located.

Chemo-ecological examinations [45] and biosensor development [46] can yield compounds perceived and used by insects for resource location. Because of their short lifetime, biosensors are useful predominantly in on-site and source tracking applications. Monitoring applications have to use sensor technology with lifetimes of several years. Thus, solid-state sensors can be tuned to marker compounds used by insects in order to detect specific resources like burnt wood.

This biomimetic approach has to face several challenges:

- Sensitivity of insect antennae is much higher than of most solid-state sensors causing a restriction of possible applications. Biomimetic long-distance forest fire detection is not possible yet because of the high dilution of smoke volatiles into free atmosphere. However, indoor applications in storage units, buildings, and industrial facilities are possible because of the comparably low dilution of smoke volatiles in the limited air space.

- Selectivity of insect antennae is much higher than of most solid-state sensors. This issue can partly be resolved by an optimization of selectivity utilizing different novel solid-state sensor production techniques like doping and nanocasting and by sophisticated operation procedures like temperature cycling [47]. Moreover, the combination of several compound group specific sensors into an array can improve discriminating power of the solid state sensor system [48].
- Processing in insect brain has to be mimicked by data processing like neural network approaches and sophisticated chemometric methods [49].
- Natural resources to be detected by insects are not completely congruent with warning situations in urban or industrial environment. Thus, not every insect-marker compound is suitable as a marker compound for a technical process. For example, α-pinene, being released by leaves/needles during forest fires [7], is not suitable for smoldering fire early warning in lignite storage units because thermal decomposition products of lignite do not contain terpenes as typical resin compounds. In contrast, other marker compounds like guaiacol derivatives [50] are highly suitable compounds for smoldering fire early warning in lignite storage units. Boundary conditions of technical processes are not identical with the natural, biological environment of the insects. This can result in different interfering compounds. For example, high nitrous oxide concentrations prove to be problematic during detection by solid-state sensors used for early fire warning during an industrial wood particle drying process [50].

A consequential application that comes into mind is to design a biomimetic sensor for the same purpose as the biosensor in coal storage units, i.e., detecting smoldering coal, but on a monitoring basis. A biomimetic solid-state sensor array on the basis of the detection of insect marker compounds [50] has been reliably working for over five years now in several industrial lignite storage units.

Another application can be gleaned from the behavior of the pyrophilic beetle *M. acuminata* after having reached the freshly burned site. Female beetles lay their eggs on stems that were not completely destroyed by fire. To be able to locate an appropriate place for egg deposition, the beetle has to be able to distinguish between different stages of heated or burned wood tissue. This ability is based on the perception of marker compounds that correlate significantly to wood heating and the temperature of the wood beneath the bark. This set of marker compounds, when detected by a semiconductor gas sensor system, can be utilized for fire warning applications detecting wood fires before they show open flame. Such applications can be adapted to wood flake driers in the wood processing industry [51]. Reducing the varying water content of wood flakes (70–50%) down to 8–6% in order to glue and press them into boards requires a large energy input.

As the drying process progresses more efficiently at higher temperatures, it would be more efficient to dry the flakes just below the threshold of self-incension. Under production conditions, temperature is at a level that ensures fire safety by

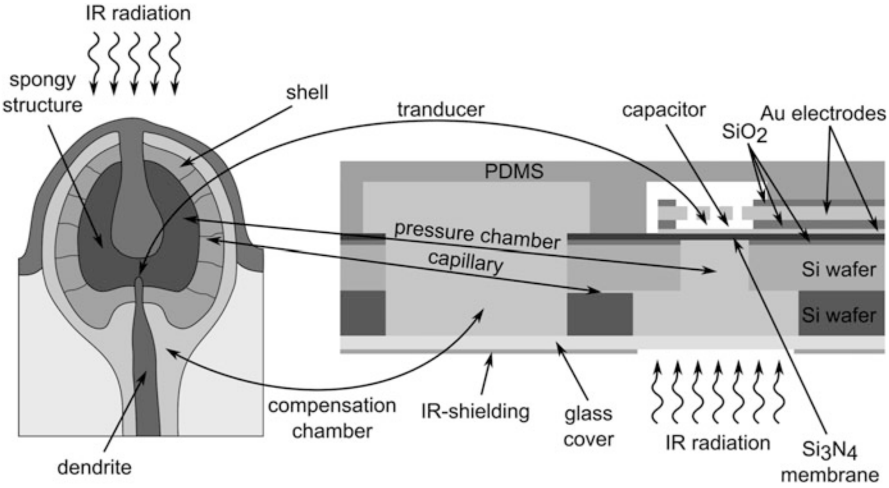

Fig. 9 Biomimetic approach to an uncooled IR sensor on the basis of IR perception by the beetle *M. acuminata*. *Left*: simplified cross section of the IR receptor in *M. acuminata*. *Right*: cross-section of the IR sensor on the basis of MEMS technology (not to scale). Modified from [52]

monitoring the air temperature and installing spark extinguishing systems. Monitoring marker compounds characteristic for heated wood just before self-incension would allow higher temperatures in wood flake driers without increasing the fire hazard. This confers the advantages of reducing energy consumption, avoiding potential loss of material due to fire, and avoiding damage due to the fire itself. As self-incension of sawdust stored in silos as a renewable energy source is one of the problems faced by modern energy plants, such systems could also be installed in biomass storage units. Moreover, fire early warning applications for wooden constructions, like warehouses and hotels are possible, whereas the relatively high-energy consumption of semiconductor gas sensors limits commercial viability in the private market.

Of course, biomimetic sensor approaches are not limited to insect olfaction. *M. acuminata* uses specialized infrared-sensing receptors based on a fluid-filled pressure cell. By absorbing IR radiation, the fluid heats up and expands, the receptor senses the resulting pressure increase using a mechanoreceptor. A biomimetic approach to this type of uncooled IR sensor using MEMS technology uses the deflection of a Si_3N_4 membrane having one electrode of a plate capacitor on top by the pressure increase inside the pressure cell (Fig. 9). A long and narrow channel connects the pressure cell to a compensation chamber.

This chamber is sealed by a thin and elastic PDMS membrane to the outside. The channel enables a slow transfer of fluid to the compensation chamber while the thin PDMS membrane maintains the pressure inside this chamber close to the ambient pressure, protecting the breaking of the Si_3N_4 membrane because of changing ambient pressure or temperature [52].

In technological applications combinations of sensors with different modalities as they occur in nature might be another field of biomimetic inspiration for meeting challenging requirements regarding dependability of sensor outputs.

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