Early forest fire detection using low energy hydrogen sensors

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ABSTRACT

The North-east German Lowlands is a region with one of the highest forest fire risks in Europe. In order to keep damage levels as low as possible, it is important to have an effective early warning system. Such a system is being developed on the basis of a hydrogen sensor, which makes it possible to detect a smouldering forest fire before the development of open flames. The prototype hydrogen sensor produced at the Humboldt University Berlin has a metal/ solid electrolyte/insulator/ semiconductor (MEIS) structure, which allows cost-effective production.

Due to the low energy consumption, an autarchic working unit could be installed in the forest. Field trials have shown that it is possible to identify a forest fire in its early stages when hydrogen concentrations are still low. A significant change in the signal due to a fire was measured at a distance of about 100m.

In view of the potential impacts of climate change, the innovative pre-ignition warning system is an important early diagnosis and monitoring module for the protection of the forests.

Keywords: North-east German Lowlands, Scots pine forests, smouldering forest fire, low hydrogen concentrations, low energy hydrogen sensor

1. INTRODUCTION

The North-east German Lowlands, which has approx. 1.6 million hectares of forest with a large proportion of medium-aged pine stands, light sandy soils with poor water storage capacity, and comparatively low precipitation rates, has one of the highest risks of forest fire in Europe, comparable with areas in Portugal [1]. Droughts during the vegetation period are common. In the Federal State of Brandenburg, forest fires in 2003, a dry year, caused damages of more than a million euros [2]. The future development of the forest fire potential will depend to a considerable extent on seasonal effects as a consequence of global climate change, and the impact this has on vegetation.

Major forest fires with disastrous effects occur frequently in drought periods, for example in California in 2009 or in Russia in 2010 [3].

In order to be able to fight forest fires effectively and to keep the area affected to a minimum, it is important to be able to identify and localise the fire at the earliest possible stage. A camera-based monitoring and optical warning system ("Fire Watch") is already being used in forests in Brandenburg. However, this is only able to identify a fire which is already producing intensive smoke or flames. Earlier warning could lead to prompter intervention and be more effective in preventing extensive damage.

While most systems determine heat, open flames, or airborne dust particles, it is also possible to detect gases released by smouldering organic matter before flames are visible. The occurrence of hydrogen during smouldering fire has been noted in the literature ([4], [5], [6], [7]. Amamoto et al. [8] pointed out that hydrogen levels are raised during the burning of a wooden building and that an increased hydrogen level is the first detectable event during such an experiment. The concentration of hydrogen created during smouldering was about 20ppm, measured in a shielded environment. To detect a smouldering forest fire, the sensor would have to reliably measure even lower concentrations of hydrogen.

A recent comparison of hydrogen sensors [9] showed the limits of commercial hydrogen sensors. None of the reported sensors was able to detect a concentration below 10ppm. Because of the low hydrogen concentration induced by smouldering fires, it was necessary to develop a much more sensitive sensor. We developed a low-energy hydrogen sensor set-up for outdoor applications with a very low detection limit, able to measure hydrogen concentrations below 5ppm. Here we present first results of field experiments in Scots pine stands.

2. METHODS

2.1 Sensor

The detection of hydrogen is a promising approach for fire detection. Other fire-detection systems, relying on smoke, heat or light, are only able to detect a fire on the basis of open flames (heat and light) or the production of relatively large amounts of smoke (measurements of airborne particulate matter).

Hydrogen produced by the pyrolysis of organic matter has good diffusion properties, making it particularly suitable for the detection of smouldering fires at an early stage. A forest fire detection system would have to be able to detect some 10-20ppm hydrogen over a forest area in order to ensure satisfactory early warning.

A prototype hydrogen sensor developed at Humboldt Universität Berlin consists of a silicon semiconductor element which can be produced industrially at low unit costs. It power consumption is a factor of 10^6 lower than so-called "low power consumption gas sensors".

The structure of the metal/solid electrolyte/ insulator/semiconductor (MEIS) is shown in Figure 1. Silicon oxide and silicon nitride insulators are grown on a silicon wafer. The thickness of this insulator is 150nm. Afterwards a 150nm lanthanum trifluoride layer is grown by physical vapour deposition. The 20nm palladium layer is produced by DC sputtering. This layer operates as gate metal. The structure differs from the "Lundström sensor" [10] because of an additional superionic conductor between the insulator and the gate layer. Due to this additional layer, the dependence of the electrical signal on hydrogen concentration is changed. In contrast to a square root dependency of the "Lundström sensor", our sensor shows a logarithmic concentration response. Details of the solid electrolyte layer can be found in [11].

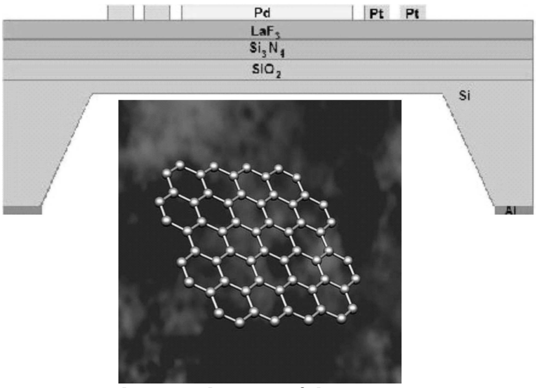

Figure 1: Schematic diagram of the capacitive sensor structure.

The final sensor structure used in our experiments was Pd/LaF3/Si3N4/SiO2/Si. This sensor chip is a capacitive element, and the capacitance depends on the voltage between gate (palladium) and bulk (silicon, ohmic contact). The capacitance was measured between the back-side aluminium contact and the gate. This structure was bonded on a ceramic heater which is used for the activation of the sensor. The sensors were activated once a day to improve the response time and the signal. Details and effects of the activation process can be found in [12]. During operation, the sensor does not need to be heated. The measurements were made at ambient temperature. The power consumption of the electronics is low, and operation with batteries is possible [13].

When hydrogen reacts with the sensor structure, the capacitance/ voltage behaviour changes (Fig. 2). Hydrogen molecules dissociate at the palladium surface and hydrogen atoms interact with the lanthanum trifluoride layer. Via this process, additional charges occur, and the chemical potential is modified. The result is a reduction in the capacitance voltage plot. The voltage shift of the sensor shows a logarithmic dependency to the hydrogen concentration [14]. Due to this relation, it is possible to measure hydrogen concentrations over a very large range. Concentrations as high as 10% (100 000ppm) can be measured and very low concentrations (< 5ppm). This is necessary for an alarm system in forests in view of the dilution effects. Details of the response to hydrogen with these sensor systems were described by [14].

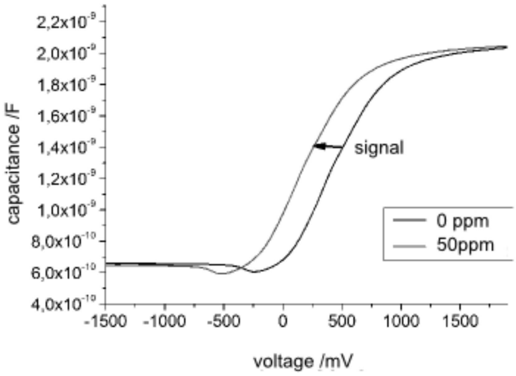

Figure 2: Change of the capacitance voltage plot due to hydrogen uptake. Hydrogen at the palladium surface reduces the potential.

2.2 Experimente

The tests were carried out at an ecological forest trial station (Eberswalde) and in pine forests in the Federal State of Brandenburg, 50km north-east of Berlin (Fig. 3).

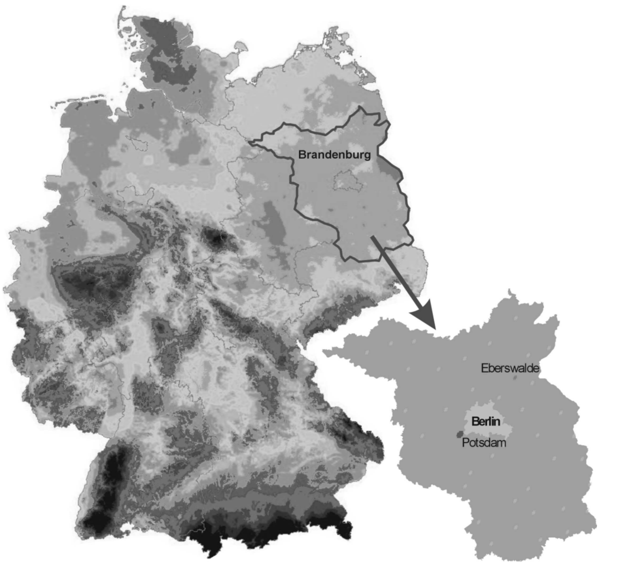

Figure 3: Map of Germany, showing the location of the Eberswalde test area.

The functionality of the sensors in the mature stands was tested in various arrays. The sensors were attached to trees at a height of 1m to 4m, initially spaced evenly at eight points of the compass around the source of a simulated smouldering fire. The aim here was to examine wind influences. In further trials, the sensors were positioned along transects, in order to examine the maximum distances from the source of the fire at which sensors were still able to detect low level changes in hydrogen concentrations (Fig. 4 a, b). The simulated source of the fire was situated at the centre of the test area.

Figure 4a: Source of fire in a mature pine stand.

Figure 4b: Forest fire sensor with antenna on a Scots pine tree.

For the field experiment, an electronic design was developed which measures the capacitance of the sensor and adjusts the applied potential in feedback mode. These electronics measure all data autonomously and are able to store the collected data. With a commercial XBee RF (radio frequency) module, a wireless communication was implemented so that it was possible to control all sensors and collect data over a large area in the forest.
Figure 5 shows the sensor signal for different hydrogen concentrations. This graph illustrates the logarithmic dependency between the hydrogen concentration and the resulting sensor signal from below 1 to 1000ppm [13].

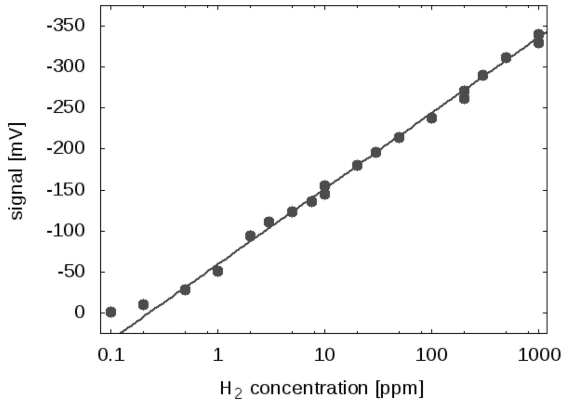

Figure 5: Sensor signal as function of the hydrogen concentration from 0.1 to 1000ppm. The sensor has a logarithmic dependency between the hydrogen concentration and sensor signal.

3. RESULTS

The distance between the sensors and the source of the fire was increased in steps, beginning with a few metres. After establishing that hydrogen could be detected at 25m, the distance was increased to 85m and then finally to 110m. The smouldering organic matter representing the source of the fire had a constant area of approx. $2m^2$, and was located at the centre of the test area.
Figure 6a shows the set-up for distances between fire and sensor of 25m to more than 100m. The corresponding signals are shown in Figure 6b. Sensors B, C and F show a significant change in signal. For these sensors the distance to the fire was 25 and 105m. Even at sensor H, at a distance of about 115m there was a small influence. The registration of response signals within 30 minutes at such distances is promising for a very early warning system in forests.

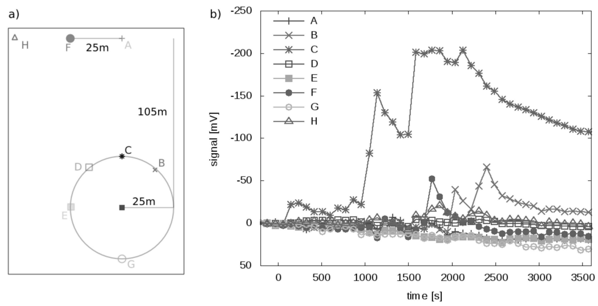

Figure 6: Experiment in the pine-forest with a sensor distance between 25m and 115m. (a) The experimental setup. (b) The sensor signals. Three sensors show a significant change (C, B and F). A small change is visible for sensor H [13].

A very close spacing of sensors in a forest is therefore not necessary. The wind in forests frequently changes direction so that gases released by a fire are transported in various directions and over considerable areas. Given the ventilation effects and entrapment of gases under the forest canopy, it seems appropriate to install the sensors in the lower third between ground level and the canopy.

4. CONCLUSIONS AND OUTLOOK

The stand structure in terms of tree species, age and spacing is not only very important with regard to forest fire hazard, but also for the positioning of the sensors in the stand. Where young pine stands are planted in rows, this creates regular wind channels, so that in this case positioning the sensors along transects seems appropriate.
In older, more open stands, a grid-like array is recommended, because in this case the changing wind direction will have a greater influence. In stands with higher canopies, the gases released by smouldering matter have more scope for spatial distribution. Wind speed and direction determines to a considerable degree the appropriate distribution of the sensors.
For the coverage of extensive forest areas, a fire must be detectable over greater distances. A sensor to sensor spacing of 100m corresponds roughly to a density of 1 sensor per hectare. In this case, a million sensors would be needed to cover all the forests in the German Federal State of Brandenburg. To reduce the number of sensors required, further experiments are planned where distance between fire and sensors are increased. The measurements have shown that with increasing wind speed it becomes easier to detect hydrogen over a distance. High wind speed is also one of the factors favouring forest fires.
The functionality of the hydrogen detection principle in forests has been established and will form the basis for further research and development.

In discussions with partners in forestry and forest environmental monitoring, interest has frequently been expressed in the early identification of risks and in risk prevention. After presentation of the results concerning the system for the early identification of forest fires, many enquiries were received about using the system. We have had to explain that the development of a full-scale system will be the goal of the second-phase project

Table 1: gives an overview of the technical progress made to date and deficits to be addressed in the future development work.

Current technical status	Deficits
• Identification of smouldering fires up to a distance of 100m • Fire identification by individual sensors, connected in a node system • 24h fire recognition, including at night • Alarm management on an external server	• Sensor is over-sensitive to high levels of air humidity. This increases the risk of false alarms. • The power consumption for electro-thermal activation (0.9mW) is still too high. • The current system is too large. • The uncertainties of the signal transfer between nodes and to the control centre.

A follow-on project beginning in July 2016 will address these deficits with the aim of developing an operational early-warning system. This will involve:

1. The development and integration of an improved hydrogen sensor with lower cross-sensitivity (<5mV for CO; <10mV for humidity) and a power rating of less than 0.01 mW for electro-thermal activation.
2. The development of a modular sensor node with multifunctional sensors, including an integrated system for forest fire early recognition on the basis of the hydrogen sensor and a stand-alone power supply.
3. A self-networking radio network of sensor nodes for use in various applications and network structures.
4. Distributed alarm management directly on the sensor nodes with intelligent adaption of the measurement intervals in accordance with the current measurements and the weather situation.
5. Evaluation of the various types of installation for the early warning system in field trials to determine the necessary network density and structure for area monitoring.

The cooperation and contributions of the project partners are shown in Figure 7. The partners are specialists in measurement electronics, communications and radio transmission, and the power supply.

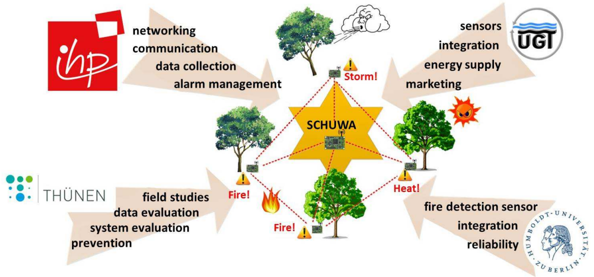

Figure 7: Contributions of the project partners.

The sensor system network will be tested in an area of pine forest (approx. 20 ha) in the north-eastern German lowland (Figure 8).

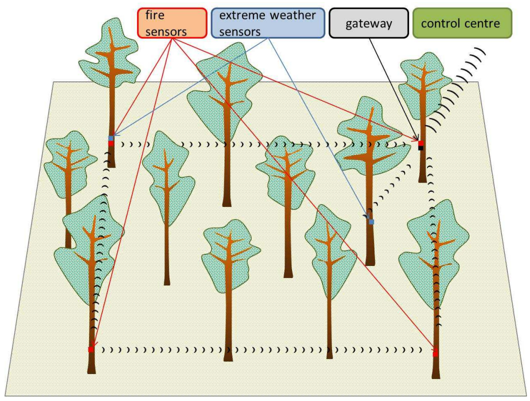

Figure 8: Demonstration field of the sensor system network in a forest area.
Users will in future benefit from the easier application and more precise and securer data transfer and alarm management. The results and insights gained during the initial phase of the project can be utilised in a range of environmental monitoring applications in order to reduce harmful impacts over larger areas. This applies in particular for:

- Reduced rate of false positives by distributed evaluation and adaptive systems
- Rapid response by efficient data transfer

- Effective energy management for maximum longevity of the sensor network
- The environmental monitoring by the sensor network automatically adapts to external conditions and the energy reserves
- Securing the data situation by alarm management
- Security against manipulation through hardware measures

An increasing degree of multi-functionality and a more complex measuring network leads to increased costs, but this is accompanied by greater benefits, e.g. by early recognition of hazards and the avoidance of damage. A cost-benefit analysis will be carried out to identify the optimum degree of multi-functionality.
The overall goal of the project is the development and testing of a prototype sensor system network for hazard monitoring and prevention in forests.

Especially in view of the potential impacts of climate change, the innovative pre-inflammation warning sensor is an important early monitoring system for the protection of the forests.

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