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Production Systems

Fertilizer monitoring using micromachined cantilever

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***Abstract**. In this study, we will create a grid of micro electro-mechanical (MEMS) sensors, which will measure the contents of soil, especially urea. This will inform the farmers about the condition of soil in real time, and thus allowing them to know how much fertilizer they need to add. MEMS sensor is placed in the soil to measure the soil content by chemical reaction with the fertilizers; its accuracy can be improved if these sensors are placed on multiple points, i.e., they are placed in a grid. In the present study, we designed micro-cantilever based gas detectors, to detect ammonia present in the fertilizers. Several designs were proposed to find the best fit for this purpose. Numerical studies have been carried out on the proposed designs, to evaluate the displacement sensitivity and the voltage developed in the piezoelectric layer, and the triangular cantilever was found to be the most sensitive cantilever for that purpose.*

Keywords: soil, fertilizer, ammonia, cantilever, deflection, stress

Introduction

A fertilizer is any material which provides nutrition to the crops and helps in proper growth of the plants (Matthews, 1994). Fertilizers provide three primary macronutrients, i.e., nitrogen (N), potassium (K), phosphorus (P); and three secondary macronutrients, i.e., calcium (Ca), magnesium (Mg), sulphur (S). Apart from these, fertilizers also provide different micronutrients like copper (Cu), manganese (Mn), iron (Fe), zinc (Zn), boron (Bo), etc. (Matthews, 1994; Islami et al., 2011). The macronutrients are consumed by plants in large quantities, hence the term 'macro'. They are also present in the tissues of the plant in a significantly higher amount than micronutrients. The most important of these macro/micro nutrients is nitrogen, mainly because it is present in proteins and DNA (Matthews, 1994; Kooser et al., 2004; Islami et al., 2011). Plants are unable to metabolize atmospheric nitrogen, hence it needs to be 'fixed' for consumption by plants. In the wild, it is achieved by bacteria and legumes, by converting it into ammonia. However, for crop production, where high yield is necessary, we have to use fertilizers to enhance crop productivity. Nitrogen is supplied to the ground in the form of ammonia or ammonia based compounds, like urea (Kooser et al., 2004; Bineva et al., 2007).

Conventionally, we have three steps to measure the soil productivity. Step 1 is soil sampling. This is manually carried out in the field, and the soil is taken out from a depth of 20cm. Topsoil is not taken, as it is not a representative sample of the whole soil in the farm Matthews (1994). Different areas of the farm are used in the soil analysis. The size of the sample should be decent, so as to obtain proper results. The next step to be taken is pretreatment of soil. This is performed for the purpose of obtaining soil extracts. It is done through sequential processes, that are drying, crushing, sieving, extracting and filtering (Matthews, 1994; Islami et al., 2011); The next step is the actual chemical analysis performed in the process. The chemical analysis is handled by trained professionals in a private or a government laboratory, on sophisticated bench instruments to obtain the concentrations of soil nutrients. In general, ultraviolet spectrometry is employed for detecting N, P and flame spectrometry or atomic absorption spectrometry for potassium (Ficarro et al., 2002). This process is time-consuming, as it takes days to get a test done. Thus we propose a novel, inexpensive and modern way for the farmer to get to know the deficiencies in the soil, to be delivered in real time. We propose to build a microcantilever-based fertilizer detection grid (Tang et al., 2004; Bineva et al., 2007).

The fertilizer used in crop production should be moderate in nature. On one hand, crop yield is compromised, if the fertilizer application is too less. On the other hand, if the fertilizer application is too high, a number of bad effects can be observed. The high amount of fertilizer content may cause the leaves to turn yellow or brown, which damages the plant. This is known as a chemical leaf burn (Jenkinson et al., 1985). The high amount of fertilizer applied can also damage neighboring water bodies, as the run-off from the irrigation goes to the nearby water body, damaging the water source in the process. Overexposure to fertilizers can lead to decrease in the organic matter of the soil. This leads to increase in the acid content of the soil. Application of a large amount of fertilizer over a long period of time can erode the topsoil completely (Jenkinson et al., 1985; Chen, 2006). Thus it is necessary to moderate the use of fertilizer to an optimum extent, so as to decrease the

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environmental impact of using fertilizer, along with ensuring maximum crop productivity.

The most common methods employed for a microcantilever (Butt, 1996; Kooser et al., 2004; Rahim et al., 2008; Firdaus et al., 2012) with a high degree of accuracy are optical, piezoresistive, capacitive and piezoelectric methods. We have employed the use of the piezoelectric method. In this method, we have utilized the piezoelectric property of ZnO (Butt, 1996; Rahim et al., 2008). This layer produces a transient charge during the cantilevers dynamic mode of operation. Since each farm has a lot of area covered by it, and the composition of soil changes from place to place, we can show that even on a single farm, no two samples are completely alike. Thus, we require to place the sensors in a grid of similar devices, so that we can have a realistic view of the deficiency or excess of fertilizers in the soil under consideration.

Working principle. The MEMS device works after the soil has been irrigated. The ammonia present in the nitrogen- based fertilizer is the main reacting agent in the process. After the fertilizer is added to the soil, and after being dissolved in water, the ammonium ion concentration is determined by injecting parts of sodium hydroxide in mixture of soil and water, and measuring the absorbance of the evolved NH_3 gas (Matthews, 1994). For the determination of urea, the fertilizer solution is first treated with urease to convert urea to NH_4^+ (Matthews, 1994; Hagleitner et al., 2001). So by measuring the concentration of NH_3 gas, we can check the concentration of fertilizers in the soil (Matthews, 1994). On the external detection surface of the SiO_2 columns, there is a thin coating of 11-mercaptoundecanoic acid, which reacts with the vapours of ammonia, providing the main deformation. This coating is also called Self-Assembled Monolayer (SAM) (Hagleitner et al., 2001). Ammonia vapours are settled upon the Self-assembled monolayer by the process of chemisorption. This provides the necessary appreciable deformation. This reaction is reversible in nature, and the deformation is directly proportional to the concentration of the ammonia vapour (Matthews, 1994; Kooser et al., 2004). This means that the output is proportional to the deformation produced, i.e. the concentration of ammonia in the soil. After the deformation, comes the process of transduction. It can be done in a variety of ways with high degree of accuracy. The different ways are: 1) Piezoresistive (Kooser et al., 2004; Rahim et al., 2008), 2) Capacitive (Senturia, 2007), 3) Piezoelectric (Butt, 1996), and 4) Optical deflection (Pandey et al., 2007).

Design. Sleeve design: The sleeve in which the device is kept needs to be permeable to air, but should prevent water from breaching it and disrupting its proper functioning. The material chosen is high density polythene fibers. The material has high tensile strength, and can easily be machined into any desirable shape. The fibers are 5-10μm thick, known as filaments. The filaments are first spun, to make them as thin as possible, and then they are bonded together by applying heat and pressure, to form the given material. Moreover, these fibers have high chemical resistance and neutral pH, so it won't react to the given basic medium.

Piezoelectric Patch Design: The material needs to be piezoelectric, and should be responsive enough to give a well-defined reading for the given deformation. The material chosen is ZnO (Rahim et al., 2008). During bending, ZnO builds up a transient charge and provides a potential between the electrodes during the static mode of cantilever functioning. Figure 1 shows the several designs tried out in our studies, namely: a) Simple cantilever; b) Sandwich cantilever; c) Triangular cantilever; d) C-beam cantilever. Table 1 provides the geometric dimensions of cantilever beam used in the numerical simulations. Yellow colored patched are the ZnO layers deposited on the cantilever.

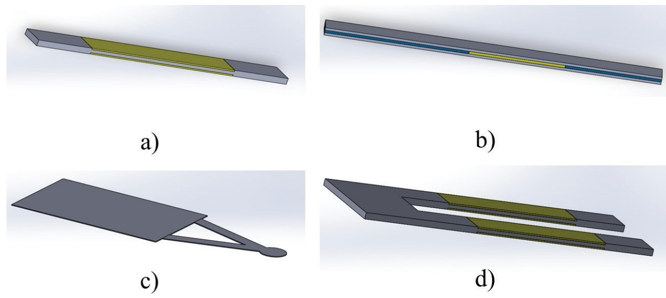

Figure 1. Different cantilever designs:
a) Simple cantilever; b) Sandwich cantilever;
c) Triangular cantilever; d) C-beam cantilever

Table 1. Dimensions of different micromachined cantilevers

Type	Length (μm)	Width (μm)	Thickness (μm)
Simple	70	8	1.8
Sandwich	70	8	1.8
C-beam	70	8	1.8
Triangular	200	25	2.0

Material and methods

Finite element analysis is carried out on different cantilever designs. The surface area is kept constant (3.2493×10^{-20} m^2) across all designs so that the loading will remain the same (8.7×10^{-6} Pa) for all the studies. Figure 1 shows the geometric model for different cantilever designs. The three-dimensional geometry of the sensor is created in SolidWorks. The modelled sensor is imported to COMSOL Multiphysics (a software tool for coupled field analysis). The structure is meshed with eight noded brick elements. All degrees of freedom are constrained at the fixed support, and the static structural analysis is carried out to evaluate the deflections and stresses induced in the cantilever. Stresses induced in turn dictate the voltage output from the piezoelectric layer. The procedure is repeated across several designs such as simple cantilever, sandwich cantilever, triangular cantilever, and C-shape cantilever.

Results and discussion

Numerical studies are carried out using COMSOL Multiphysics. Static structural analysis is carried out to evaluate the deflections and stresses induced in the cantilevers. Several sensors were designed and the structural analysis is carried out for all the designs. Figure 1 shows the different cantilevers designed for sensing ammonia. The Tip deformation and maximum stresses are evaluated using FEM analysis. Figure 2 shows the contour plot of stresses induced in different cantilevers. It can be noticed that Triangular cantilevers provide an order of magnitude enhancement in the stresses induced in the structure.

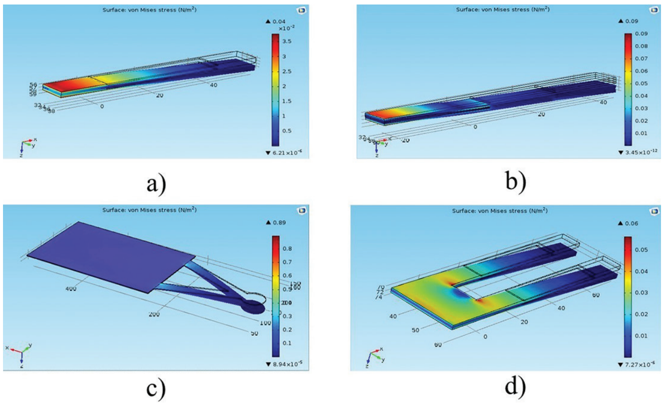

Figure 2. Stress induced in different cantilever designs subjected to a uniform loading: a) Simple cantilever; b) Sandwich cantilever; c) Triangular cantilever; d) C-beam cantilever

The tip deflections of the cantilever are evaluated. Table 2 provides the tip deflection and stresses induced in the cantilever beam under different configurations with the same loading conditions. It can be noticed that increase in the displacement sensitivity of the Triangular cantilevers is an order of magnitude higher than other configurations.

Table 2. Deflection and stress induced in different micromachined cantilevers subjected to uniform loading

Type	Deflection (nm)	Stress (Pa)
Simple	0.64	0.04
Sandwich	1.32	0.09
C-beam	1.48	0.09
Triangular	47.32	0.89

As we can see from the above results, the most suitable cantilever for ammonia detection is Triangular type of Cantilever. It gives the maximum displacement due to ammonia adsorption on 11MUA. The cantilever has uniform loading of 8.7×10^{-6} Pa.

Furthermore, Triangular Cantilever has better sensitivity using optical deflection sensing, and the laser would be spotted and reflected by the circular part in front of the beam. Even a ZnO layer can be coated on the beam which acts as a piezoelectric layer, the voltage can be tapped out from the same. Coupled field simulations are carried out by considering the properties of ZnO (Bhatia et al., 2016), to evaluate the voltage developed in the piezoelectric layer. Table 3 provides the voltage developed in the ZnO layer corresponding to deflection of the cantilever and the stress induced in the piezoelectric layer. It can be noticed that voltage developed with a simple cantilever configuration is the lowest (91μV) on the other hand triangular cantilever provides two orders of magnitude higher output voltage (6.76 mV) in comparison to others.

Table 3. Voltage developed in piezoelectric layer for different micromachined cantilevers

Type	Voltage (mV)
Simple	0.091
Sandwich	0.189
C-beam	0.211
Triangular	6.760

This device can be commercially manufactured, as the materials chosen are easy to manufacture and are inexpensive. When developed, they will significantly cut down on the time and effort required for evaluating the nutritional deficiencies of the soil. Conventionally, soil tests are done at the start of the sowing season, and the fertilizers are added throughout the season based upon the soil tested at that time. However, with these devices, we can change the fertilizer application dynamically, by noticing the change in chemical constituents in the soil. It gives the farmers greater amount of control over their production process. Also, this can be connected with the dedicated app so as to alert the farmer automatically if there is some problem in the soil. This will reduce the human effort of the farmer considerably. This can also be manufactured as a probe and connected to Internet of Things (IOT) so as to operate the farms without any human involvement, as chemicals present in some fertilizers are carcinogenic and are dangerous for humans. Even ammonia is harmful for the farmers in excess volumes. Devices like these could revolutionize the way of farming, as using MEMS farms can be easily monitored, and could pave the way for the beginning of smart farming, which can include automatic irrigation, fertilizers dispenser, automatic seed sowing and crop cutting.

Conclusion

MEMS sensor for ammonia in the fertilizer was designed. Several cantilever designs are proposed and numerical analysis was done on all the structures. The structural deflection and voltage output from the piezoelectric layer are evaluated. It was observed that triangular cantilever is the most sensitive both from the deflection and the voltage output from the piezoelectric layer, hence triangular configuration is the most preferred in comparison to others. This study can be further extended for other chemicals in the fertilizers like Phosphorus and Potassium so that we can get the real-time results for the amount of fertilizers present in the field.

References

Bineva I, Voicu R, Dinescu A, Gavrila R, Muller R, Esinenco D, Bucur B, Diaconu M and Radu L, 2007. SiO_2 microcantilevers designed for biosensing: Experiments and simulations. Romanian Journal of Information Science and Technology, 10, 13-23.

Butt HJ, 1996. A sensitive method to measure changes in the surface stress of solids. Journal of Colloid and Interface Science, 180, 251-260.

Chen JH, 2006. The combined use of chemical and organic fertilizers and/or biofertilizer for crop growth and soil fertility. International workshop on sustained management of the soil-rhizosphere system for efficient crop production and fertilizer use, October 16-20, Bangkok, Thailand.

Bhatia D, Sharma H, Meena RS and Palkar VR, 2016. A novel ZnO piezoelectric microcantilever energy scavenger: Fabrication and characterization. Sensing and bio-sensing research, 9, 45-52.

Ficarro SB, McCleland ML, Stukenberg PT, Burke DJ, Ross MM, Shabanowitz J, Hunt DF and White FM, 2002. Phosphoproteome analysis by mass spectrometry and its application to saccharomyces cerevisiae, Nature biotechnology, 20, 301.

Firdaus SM, Omar H and Azid IA, 2012. High sensitive piezoresistive cantilever mems based sensor by introducing stress concentration region (SCR). Finite element analysis-new trends and developments. 1-24, InTech.

Hagleitner C, Hierlemann A, Lange D, Kummer A, Kerness N, Brand O and Baltes H, 2001. Smart single-chip gas sensor microsystem. Nature, 414, 293.

Islami N, Taib S, Yusoff I and Ghani AA, 2011. Time lapse chemical fertilizer monitoring in agriculture sandy soil. International Journal of Environmental Science & Technology, 8, 765-780.

Jenkinson D, Fox R and Rayner J, 1985. Interactions between fertilizer nitrogen and soil nitrogen the so-called priming effect, European Journal of Soil Science, 36(3), 425-444.

Kooser A, Gunter RL, Delinger WD, Porter TL and Eastman MP, 2004. Gas sensing using embedded piezoresistive microcantilever sensors. Sensors and Actuators B: Chemical, 99, 474-479.

Matthews E, 1994. Nitrogenous fertilizers: global distribution of consumption and associated emissions of nitrous oxide and ammonia. Global Biogeochemical Cycles, 8, 411-439.

Pandey AK, Pratap R and Chau FS, 2007. Influence of boundary conditions on the dynamic characteristics of squeeze films in mems devices. Journal of Microelectromechanical Systems, 16, 893-903.

Rahim RA, Bais B and Majlis BY, 2008. Design and analysis of mems piezoresistive SiO_2 cantilever based sensor with stress concentration region for biosensing applications. IEEE International Conference on Semiconductor Electronics, November 25-27, Johor Bahru, Malaysia.

Senturia SD, 2007. Microsystem design, Kluwer Academic Publishers Norwell, MA, USA.

Tang Y, Fang J, Yan X and Ji HF, 2004. Fabrication and characterization of SiO_2 microcantilever for microsensor application. Sensors and Actuators B: Chemical, 97, 109-113.