Capacitive humidity and dew-point sensing: Influence of wetting of surface-attached polymer monolayers on the sensor response

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ABSTRACT

Polymer monolayers with controlled hydrophilicity and thus varying surface wetting properties are photochemically attached to the surfaces of capacitive humidity/dew point sensors. In the first step, a self-assembled monolayer of a photoactive benzophenone silane is attached to the surface of an interdigitating electrode (IDE) array. During a brief UV-irradiation polymers ranging from a highly fluorinated polyacrylate, which is very strongly non-polar, to highly polar polymers such as poly-N-dimethylacrylamide, are attached to the sensor surfaces to form covalently attached polymer monolayers. The effect of the hydrophilicity/wettability of different monolayer coated surfaces on the response of the sensor against deposited water drops, which serve as a simple model for dew formation, is studied. Subsequently, the performance of the different surface-modified sensors in humidity and dew point measurements under different environmental conditions is investigated. A model is proposed as to how the water adsorption and surface wetting behavior controls the performance of the sensor.

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1. Introduction

Humidity is one of the most frequently measured physical quantities [1]. Knowledge of the environmental humidity is important for various industrial or agricultural applications, for example, for air conditioning of cars or houses, supervision of food quality and storage [2] or in the field of meteorology [3,4]. For many practical applications the dew point, at which condensation and the formation of a liquid water phase occurs is an important parameter [5].

The development of microelectromechanical systems (MEMS) allowed humidity sensing devices to be miniaturized, making them faster, cheaper, more robust and potentially even more sensitive [1]. So far several miniaturized dew-point detection methods have been reported. Among them is the chilled mirror dew-point hygrometer, whose principle is based on the optical detection of condensed water droplets on a cooled sensor surface [6,7]. Another method detects the dew-point by sensing a change in heat conduction behavior of a thin silicon nitride membrane at the condensation onset [8]. A capacitive method for the dew point determination was presented by Weremczuk et al. [9]. Here the condensed water molecules decrease the sheet resistance of a polymeric sensing layer. The change in sheet resistance induces a capacitance change between the fingers of interdigitated electrodes (IDE). The advantages of such capacitive approach over the previously mentioned optical and thermal methods, is the relatively simple chip design and fabrication as well as no complex optical setup is required.

The capacitive sensing approach is a very common way to measure the relative humidity, which is then used for dew-point calculation [1,6]. Much effort has been directed at improving the capacitive response by tuning the properties of the sensor surface coatings. An important route here is to increase the surface/air contact area in order to enhance the absorption of the water molecules [10–13]. For instance, Lee et al. [10], increased the contact area by coating the sensor surface with polyimide nanograss structures, fabricated by plasma etching. Wang et al. [11] reported enhanced sensor performance, by using the ordered macroporous silicon array as a sensing layer. Moreover, they stated that, a 95 nm thin film coating of tantalum pentoxide (Ta_2O_5) on the porous surface further enhanced the performance. It was suggested that this improvement was caused by the hydrophilic properties of the coating. However, the system they used is rather complex and therefore it is difficult to judge to what extend the sensor performance was improved by varying the surface wettability. Another observation on surface wetting impact on relative humidity sensing was reported by Dabhabe et al. [14]. The authors achieved better sensitivities at lower RH ranges by making a PMMA coating hydrophilic using an Argon plasma-treatment.

Despite the fact that several publications indicate that surface hydrophilicity plays an important role in the sensor sensitivity, a
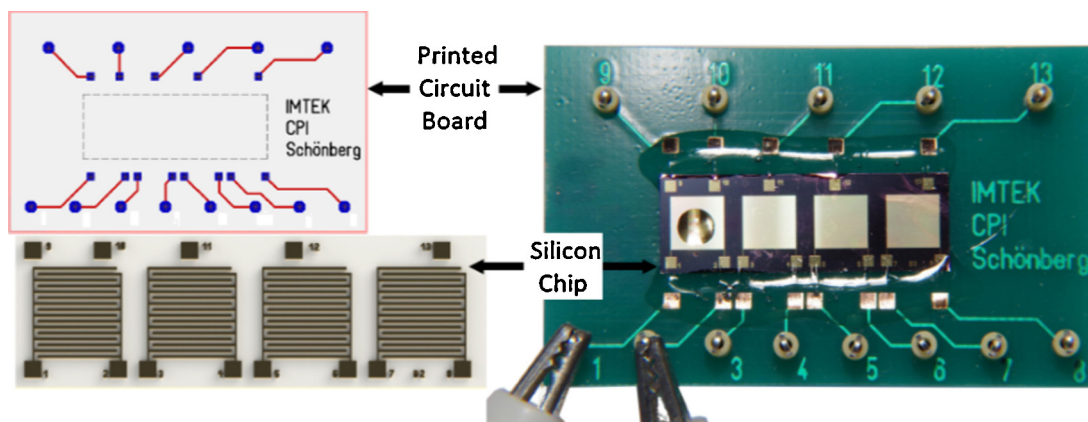
Fig. 1. Schematic layout and photograph of the generated dew-point sensor. The sensor is composed of a silicon chip mounted on a PCB. Each silicon chip carries four independent IDE units.

detailed understanding is still lacking. In this work we want to address this problem and investigate capacitive dew-point sensors with surfaces, which exhibit controlled differences in the hydrophilicity and thus wetting behavior. This is achieved by attaching polymer monolayers through a photochemical immobilization process to the surfaces of interdigitating electrode arrays. To better understand the sensor response to dew formation we firstly investigate the electrical capacitance change (ECC), induced by the deposition of water drops on the sensor surface as a function of the contact angle of the surface and the droplet volume. The changes of the capacity as a function of changes in the humidity and/or surface-temperature as a function of the surface properties of the monolayers were subsequently investigated.

2. Materials, fabrication and measurements

2.1. Sensor structure

A schematic of the dew-point sensor prototype is shown in Fig. 1. The silicon chip has four independent sensing areas, each of them contains an array of the interdigitated gold electrodes (IDE). The 200 nm thick interdigitated electrodes have a width of 10 μm and are 5 μm apart from each other, which results in a 66% area coverage by the electrodes. The electrodes are covered by a 600 nm SiO_2 passivation layer in order to prevent leakage currents between the electrodes.

Connection to the measurement device is achieved by using measurement tips (Farnell GmbH, Germany), connected through copper lines to copper bond pads, which are connected to corresponding pads on the silicon chip by aluminum wires using a wedge–wedge bonding machine 5430 (F&K Delvotec Bondtechnik GmbH, Germany). To shield the wires and pads from environmental

impact, a two-component adhesive, Loctite 3430 (Henkel AG & Co. KGaA, Germany) was used.

2.2. Silicon chip fabrication

For the chip fabrication (1 0 0) oriented silicon wafers were cleaned in conc. H_2SO_4/H_2O_2 (30%) 3:1 (Caro's acid) and dipped into hydrofluoric (HF) acid to remove the native oxide. A 200 nm thick Si_3N_4 layer was then deposited using low pressure chemical vapor deposition (E1200 HT 250/60-4, centrotherm photovoltaics AG, Germany). In a standard photolithography and lift-off process the electrodes and bond pads were generated from 20 nm chromium and 200 nm gold layers by physical vapor deposition (Univex 500, Oerlikon Leybold Vacuum GmbH, Germany). After resist removal, a 600 nm thick silicon dioxide passivation film was grown on the chip surface by utilizing plasma enhanced chemical vapor deposition (PC 310, SPTS Technologies Limited, UK). In a second photolithography step followed by reactive ion etching (ICP Multiplex dry etcher, SPTS Technologies Limited, UK) the silicon oxide on top of the bond pads was removed.

2.3. Surface modification

To tune the sensor surface properties the silicon chip was coated with surface attached monolayers of polymers as schematically shown in Fig. 3. The polymers were synthesized according to earlier reported procedures [15,16]. In order to bind the polymer monolayers to the silicon oxide surfaces firstly a monolayer of 4-(3′-chlorodimethylsilyl) propyloxy benzophenone was immobilized onto the silicon chip [15]. The polymer of interest (Fig. 2) was then dissolved in its respective solvent (Table 1) with a concentration of 15–20 mg/ml. The polymer solution was then spin-coated
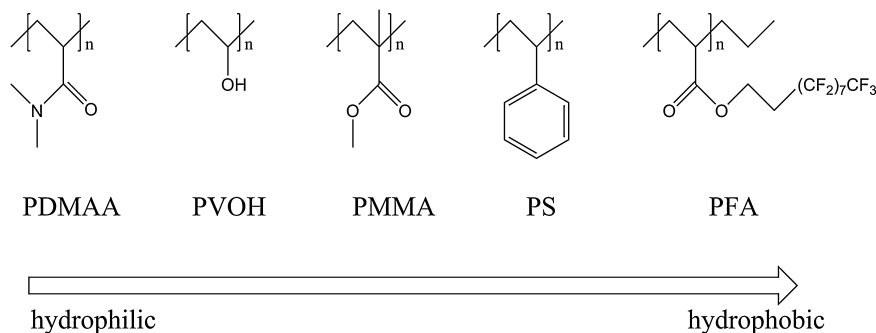

Fig. 2. Chemical structures of the polymers used as coating of the sensing surfaces.