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Sensitivity evolution and enhancement mechanism of porous anodic aluminum oxide humidity sensor using magnetic field

S.W. Chen, O.K. Khor, M.W. Liao, C.K. Chung*

Department of Mechanical Engineering and Center for Micro/Nano Science and Technology, National Cheng Kung University, Tainan 701, Taiwan, ROC

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ABSTRACT

Capacitive sensors based on anodic oxide aluminum (AAO) film provide a fast and reliable means of sensing humidity. Moreover, the water molecules under a magnetic field preferentially form water clusters in which the dipole moments of the water molecules have a more orderly arrangement. In this article, we have investigated the sensitivity enhancement and its mechanism of the AAO humidity sensor by performing the sensing operation in the presence of an NbFeB magnet. The results show that the application of a magnetic field with a strength of 0.058 T yields a linear-like relationship between the capacitance and the relative humidity (RH) even under low RH of 25–45%. The sensitivity performance at low-to-high RH conditions arises because the magnetic field leads to a more orderly arrangement of the water molecules in the pores of the AAO film so as to increase the dielectric constant. Thus, the proposed method and mechanism suggest significant potential for enhancing the sensitivity and linearity of the capacitive AAO sensor from low-to-high RH.

1. Introduction

The detection and control of humidity is an important task in many industrial, agricultural and environmental monitoring applications. Various materials are used as a probe for monitoring relative humidity (RH), including ceramic [1,2], glass-ceramic [3], semiconductor [4,5], polymer [6], and porous anodic oxide aluminum (AAO) [7–9]. Among these materials, sensors based on porous AAO measure the humidity by detecting the change in the dielectric property of the AAO film as the water molecules are absorbed on its surface. Compared with other humidity sensors, AAO sensors have a faster and more reliable response [10,11]. In addition, AAO sensors have a high corrosion resistance, good thermal stability and excellent mechanical strength as well as high sensitivity under high RH conditions. Additionally, many types of humidity sensors based on capacitive, resistive, mass-sensitive and electromagnetic features have been published [12–14]. Among them the capacitive and resistive types have attracted more attention meanwhile capacitive sensors are much more popular and commercial. Regarding capacitive sensing mechanism, Khanna and Nahar [12] and Morimoto et al. [15] reported that water molecules initially chemisorbed on the metal oxide and two hydroxyl groups were formed per water molecule. Then the following water molecules physically bound with this hydroxyl groups by hydrogen bonds to form the first physisorbed layer. Therefore at low RH condition (<40%), the capacitance is low and varies non-linearly with the humidity [10,12,16,17]. Some studies have shown that by decreasing the thickness of the AAO film [10], increasing the current density [7] or using H_2SO_4 solution rather than oxalic acid [12], the sensor has a near linear log-normal relationship between the capacitance and the RH even under low RH conditions. However, the log-normal relationship prevents the humidity from being measured with a high degree of accuracy. In addition, Kim et al. [17] showed that the sensitivity and linearity could increase by changing the shape of device and pore size of AAO. However, the linearity is still too low at the low RH condition (<40%). It wonders whether there is a method to increase the sensitivity and linearity of capacitive AAO sensors under low humidity conditions.

Ibrahim [18] and Pang and Bo [19] showed that water molecules under a magnetic field preferentially form water clusters in which the dipole moments of the water molecules have a more orderly arrangement than those without magnetic field treatment. Moreover, the conductivity and dielectric constant of the water molecules are also increased. It is thus of interest to investigate how magnetic field can influence the sensitivity evolution of AAO humidity sensors. In this article, a magnet is combined with a capacitive AAO humidity sensor and experiments were then performed

* Corresponding author at: Department of Mechanical Engineering, National Cheng Kung University, Tainan 701, Taiwan, ROC. Tel.: +886 6 2757575x62111; fax: +886 6 2352973.
E-mail addresses: ckchung@mail.ncku.edu.tw, ckc830474@yahoo.com.tw (C.K. Chung).

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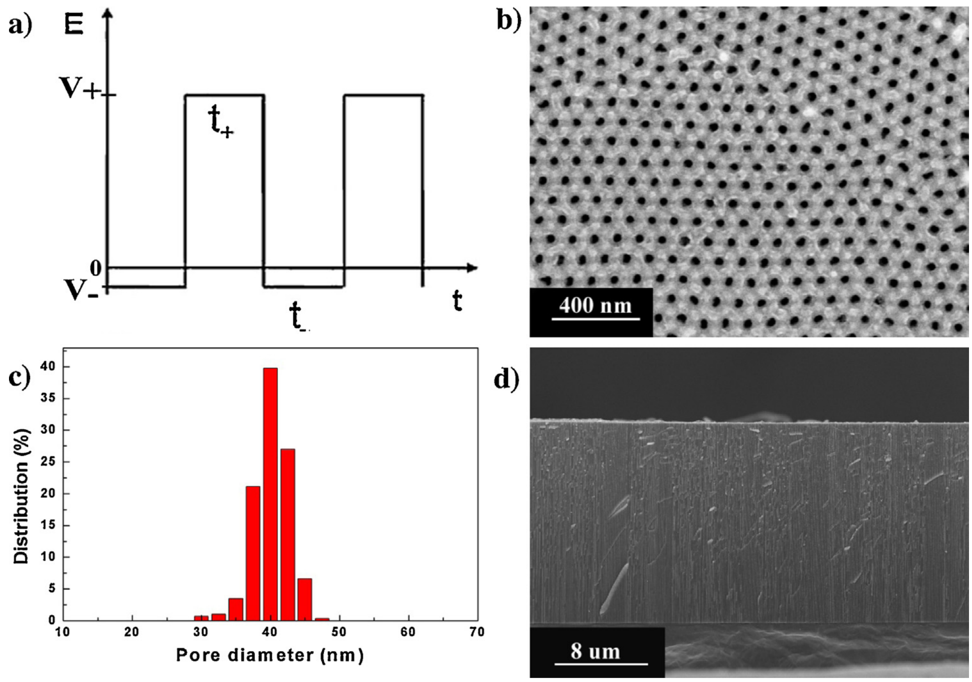

Fig. 1. (a) The relationship between the applied potential difference (*V*) and the corresponding current (*I*) as a function of time (*t*) at HPA, (b) SEM micrographs of porous AAO film after deposition Pt thin film obtained by oxalic acid of 0.3 M, (c) the distribution of pore size with a mean value standard deviation of 41.2 ± 2.7 nm, and (d) the thickness of AAO film with anodization time for 2 h.

to examine the effect of the external magnetic field on the relationship between the capacitance and the RH. The results show that the sensor yields a higher capacitance under high RH condition than one with no magnet. More importantly, the magnetic field causes the sensor to have a linear-like relationship between the capacitance and RH under low humidity condition.

2. Experimental details

2.1. Fabrication of AAO humidity sensor

The capacitive humidity sensor was fabricated based on a porous AAO film prepared using a two-step hybrid pulse anodization (HPA) process, which can diminish Joule heat dissolution and improve distribution uniformity of AAO [20,21]. In brief, a high-purity aluminum (Al) foil (99.99%, Alfa Aesar, USA) (2.5 cm × 2.5 cm) was electro-polished chemically and then placed in a holder (diameter = 1.4 cm) with an exposed area of 1.54 cm^2. Formation of AAO was performed by means of the potentiostat (Jiehan 5000, Taiwan) and the three-electrode electrochemical cell with the platinum mesh as the counter electrode, with the aluminum foil as the working electrode, and with saturated calomel electrode (SCE) as the reference electrode. The first step of the anodization process was performed in 0.3 M oxalic acid at 25 °C for 2 h using HPA, which is mainly composed of a positive potential difference (V+ = 40 V) for 1 s and a small amount of negative potential difference (V− = −2 V) for 1 s, as shown in Fig. 1(a). The anodic oxide layer was then chemically removed to leave the pre-textured Al_2O_3 on Al surface as a self-assembled mask. The second step of the anodization process was then conducted to get the AAO sample under the same conditions as those used for the first.

2.2. AAO characteristics analysis

The resulting AAO film was observed using a Scanning Electron Microscope (AURIGA Zeiss, Germany). Fig. 1(b) and (c) show the plane view of SEM micrographs of the porous AAO film and the distribution of pore size. It can be observed that the formed pores orderly arranges. The distribution of the pore size in diameter can be obtained by commercial software (Image J) and it is mainly distributed within 30 nm ∼ 48 nm with the mean value and standard deviation of 41.2 ± 2.7 nm. Fig. 1(d) shows the cross section of AAO film for thickness evaluation. It is about 17.1 μm and fixed for the study of magnetic effect on humidity sensing of AAO.

2.3. Experimental setup of humidity sensor

In fabricating the humidity sensor, a Pt thin film electrode was deposited on one side of the AAO film via a sputtering process with 20 mA for 180 s by Auto Fine Coater (JFC-1600 JEOL, Japan) and did not cover the AAO pores. The sensor was placed into a proprietary measurement system to investigate the variation of the capacitance with the RH level at various field strengths. As shown in Fig. 2, the system mainly included a computer, LCR meter, commercial humidity sensor and two chambers. Through adjusting the flows of dry air and wet air into chamber 1, a controllable

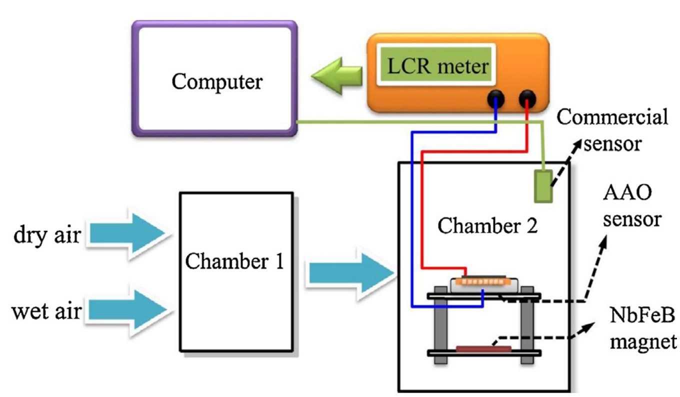

Fig. 2. Schematic diagram of the experimental system used to characterize fabricated humidity sensor.