

Capacitive Humidity Sensors Using Highly Durable Polyimide Membrane

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ABSTRACT

Humidity sensors used in automatic windshield defogging controls contribute to the improvement of fuel consumption. The optimum control of air conditioning systems can be realized by adding humidity information to conventional systems which have used only temperature information.

While resistive humidity sensors have been widely used, their sensing range and responsiveness are observed as issues. Resistive sensors cannot function at a humidity range of around 100% RH as well as at a low temperature range, and have a low response rate to sudden changes in humidity. It is considered that resistive humidity sensors will be replaced with capacitive ones which have a wide sensing range and high responsiveness. However, since capacitive sensors use macromolecule organic materials for their humidity sensing membranes, characteristic changes caused by two factors in a high temperature and high humidity environment are concerns: the deterioration of the membrane itself, and the decrease of the adhesive strength between the membrane and the underlying layers.

This paper describes a newly developed capacitive humidity sensor with high durability by suppressing hydrolysis and swelling of membranes which cause characteristic changes in a high temperature and high humidity environment. The main development processes are selection of polyimide as a basic organic material, the addition of fluorine atoms of hydrophobic molecules, the extension of the molecular repeat units and the formation of the cross-linked structure to molecular ends. In addition, silane coupling agents is used to increase the adhesive strength of the membrane, thus realizing capacitive humidity sensors for automobile use.

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INTRODUCTION

Automobiles have been recently required to save energy in order to prevent global warming. With the spread of hybrid vehicles and engine stop/start systems in the field, the application of systems that stop the engine when the vehicle is stopped or moving at a crawl in order to improve fuel efficiency, is increasing.

Car air conditioners operate in all seasons to keep the cabin temperature cool in summer and warm in winter. However, when engines stop, compressors which are driven by the engine also stop in summer, and the quantity of cabin heating energy supplied from engines themselves decreases in winter. Therefore engines are forcibly operated to maintain a comfortable temperature by driving air conditioners. Additional energy is consumed and thus creating problems of fuel efficiency.

This paper describes a newly developed humidity sensor that is required to realize a system which maximizes comfort and improves fuel consumption by adding humidity information to improve the control of conventional car air conditioning systems that used only temperature information as the main parameters of the cabin environment.

ROLE OF HUMIDITY SENSORS

Until recently the improvement of air conditioning systems to improve comfort and convenience has relied solely on temperature information provided to the system. Air conditioning systems equipped with humidity sensors started being used in the field to achieve better fuel consumption through improvements of both the dehumidification function in summer and the defogging control in winter. However, it is

very difficult to realize efficient controls by using only cabin temperature information.

In summer, for air conditioning systems without humidity sensors, the system cannot maintain a comfortable humidity level because the dehumidification function stops when the compressor stops. However, a system with the humidity sensors can maintain a comfortable level because the system operates with on/off switching control of the compressors based on the information of humidity sensors even when the engine is stopped. In winter, to reduce the heating load, the air conditioning system in conjunction with the engine controls defogging of the windshield using humidity sensors in addition to reducing ventilation loss by increasing the recirculation rate. By adding humidity information, the control of humidity in summer and defogging in winter can minimize the operation of compressors and the engine, and lead to improved fuel consumption without loss of comfort. In particular, in order to prevent energy loss, it is necessary to sense the humidity around windshields so as to prevent windshields from fogging up in winter.

CURRENT ISSUES

Automobile humidity sensors used in the field are mainly resistive ones. Resistive sensors monitor the impedance change of the humidity sensing membrane absorbing water molecules responding to ambient humidity changes. Impedance changes occur as a change in the quantity of ions, such as the alkaline metals, anchored in the sensor membrane. The ions become capable of moving in the membrane due to the absorption of water molecules. Resistive sensors that use polymer membranes containing ammonium salt etc. encounter three main types of issues. The first issue is that the sensing range of the temperature and humidity is small. Resistive humidity sensors cannot function at around 100% RH and below 0 °C. The second issue is the dissolution of the humidity sensing membrane. When water beads are formed on the humidity sensing membrane due to dew condensation and the beads drop off, movable ions in the membrane dissolve into the beads and also drop off. The third issue is the slow responsiveness to changes in the surrounding humidity. It takes time for water molecules to diffuse into the membrane because the membrane thickness of resistive sensors is over 10 μm .

In order to solve these issues, capacitive humidity sensors have been developed in recent years. The capacitive sensors monitor changes in the relative permittivity of membranes in response to humidity changes in the surrounding environment. Polyimide or cellulose is used for humidity sensing membranes of capacitive sensors. The relative permittivity of the polyimide in a humidity membrane is about 3, and that of water molecules is about 80. If membranes absorb water, changes in the apparent relative permittivity occur due to water molecules. As a result, the humidity can be sensed using this technology.

As shown in [Figure 1](#), capacitive sensors can function at ranges of around 100% RH and below 0 °C. The membrane will not dissolve even if water beads are formed on the membrane due to dew condensation etc. because water resistive materials like polyimide are used for the humidity sensing membrane. Thus, as shown in [Figure 2](#), it has become possible to install the capacitive sensors at the optimum position for sensing humidity on windshields to prevent fogging. In addition, the responsiveness of the sensors themselves becomes extremely quick to humidity changes because the membranes are very thin, only about 3 μm in thickness, and the responsiveness of the system itself is also significantly improved because the sensors can be installed on the windshield. In this way, the material of the membrane is a core technology for humidity sensing.

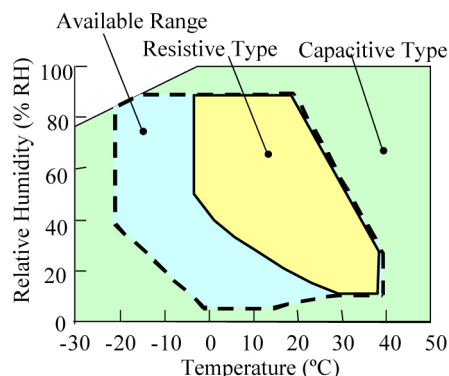
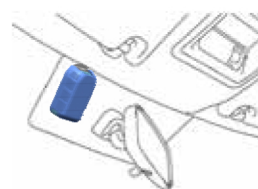
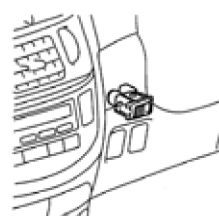


Figure 1. Sensing Range of Humidity Sensors

Resistive Sensors

Capacitive Sensors



Side of Center Console

Back of Rearview Mirror

Figure 2. Installation Position of Resistive and Capacitive Sensors

INVESTIGATION OF CAUSES (HUMIDITY SENSING MEMBRANE)

It has been observed that capacitive sensors with polyimide sensing membranes often cause characteristics changes in endurance testing, particularly in a high temperature and high humidity environment. It is considered that changes in characteristics are caused by the deterioration of macromolecule organic materials that constitute humidity sensing membranes due to water absorption. The main causes are assumed to be hydrolysis and swelling of sensing membranes. [Figure 3](#) shows the change in the capacitance

before and after endurance testing is performed in a high temperature and humidity environment (65 °C, 90% RH) using typical polyimide as the membrane material. The change in characteristics of the capacitances has two modes: an increase of the capacitance across the entire humidity range, and a significant capacitance increase in high humidity ranges. It is assumed that hydrolysis is a potential cause of the capacitance increase across the entire humidity range, and swelling is the main factor of the significant increase in high humidity ranges.

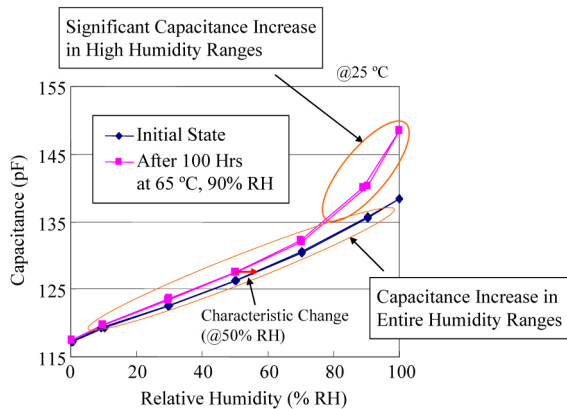


Figure 3. Capacitance Changes Before/After Endurance Testing

Regarding hydrolysis, it is assumed that the capacitance increase across the entire humidity range is caused by an increase of polar groups (the absorption site of water molecules) as a consequence of breaking molecular chains in response to the reaction between imide groups (a part of polyimide) and water molecules (Figure 4). Figure 5 shows analysis data of the FT-IR of polyimides before and after 100 hours in a high temperature and high humidity endurance testing. Upon differential analysis of polyimides before and after the endurance testing, the increase in polar groups is confirmed by an observed peak of acid anhydride resulting from hydrolysis.

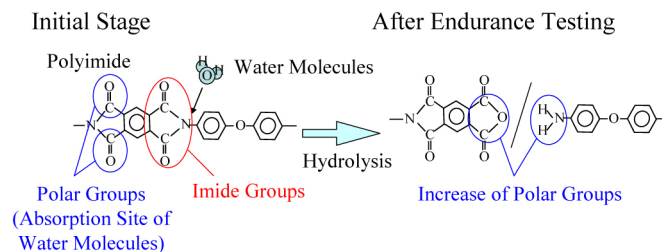


Figure 4. Polar Group Increase by Hydrolysis

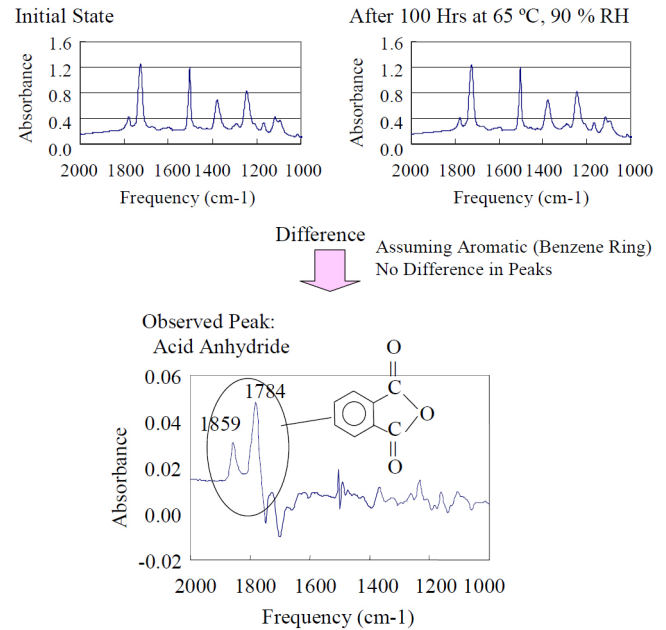


Figure 5. Analysis of FT-IR Before/After Endurance Testing

In regards to swelling, it is assumed that the clustered water molecules enter into a molecular interchain (which exists around the polar groups increased as a result of hydrolysis in a high temperature and high humidity environment) and expand the initially vacant space of the molecular interchain, and consequently, their entry by absorption results in the creation of the expanded absorption space and the expansion of the membrane volume (Figure 6). Next, with regards to the significant increase of membrane capacitance in high humidity ranges, it occurs due to a change of water molecules from surface absorption to clustering at the inside of the absorption site. Thus, the capacitance significantly increases when performing sensing in high humidity ranges. When clustering of water molecules begins, protons conductivity occurs in water molecular ions, and electrostatic loss increases. As shown in Figure 7, it is considered that water molecules become clusters because the electrostatic loss significantly increases after endurance testing in high humidity ranges.

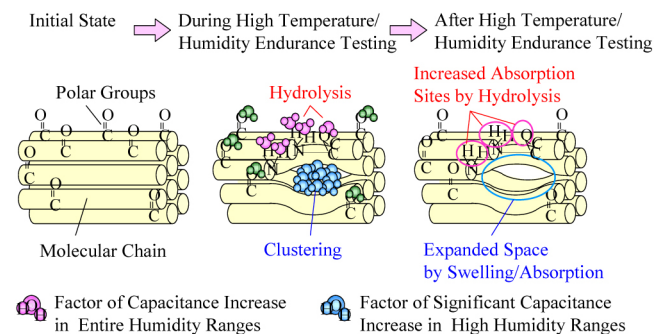


Figure 6. Swelling by Clustering of Water Molecules