Manufacturing Technology for Functional Material Films for Automotive MEMS Sensors

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We describe in this article MEMS sensors for automotive applications and related functional material films, a deposition technology for which we have developed.

The performance of automobiles is enhanced by their control systems, leading to reduced fuel consumption, higher safety, and other advantages. A MEMS sensor is an essential component of a control system because it can detect environmental changes and feed this information back to the system. The importance of automotive MEMS sensors is increasing due to the design requirements for next-generation automobiles, such as self-driving and all-electric vehicles. It is anticipated that by applying a variety of functional materials, a MEMS sensor with new functions will be realized. More specifically, this article introduces the PZT and VOx functional material films that have been developed by the authors. Both films are deposited by the sputtering method, demonstrating that films characterized by excellent performance can be obtained by applying a unique sputtering and process technology.

1. Introduction

By revenue, the size of the global automotive industry reached U.S. $2.3 trillion (in 2017) and is expected to keep growing at an average annual rate of around 2.7%. Of this amount, on-board electronic devices account for $142 billion with an average annual growth rate of 7%, and within this amount, on-board sensors account for $11 billion with an average annual growth rate of 13%[1,2], which indicates a promising future for on-board sensors.

One area that has been particularly important to the development of the automotive industry has been the improvement in performance of control systems. Control systems have helped automobiles achieve higher fuel efficiency, lower emissions, and enhanced safety, as well as improved comfort and convenience. Among the electronic control unit (ECU), sensors, and actuators that make up control systems, the sensors play an indispensable role in controlling an automobile in terms of environmental and safety considerations. The number of sensors installed in each automobile has been increasing year after year, with some models being equipped with over 100 sensors[3, 4].

Sensors themselves have also been changing. Whereas mechanical sensors were once the mainstream, the use of micro-electromechanical system (MEMS) technology has enabled highly precise measurements[3]. A MEMS is a complex electronic component that combines micron-level miniaturized mechanical parts and sensors with electronic circuits, and is manufactured using micro fabrication technology to create these components on a substrate[5]. MEMS technology enables the creation of sensors that are small yet offer high performance and high reliability. Additionally, various improvements have also made it possible to commercialize sensors that can be used under harsh environments, such as high temperatures[6].

For the majority of on-board sensors, MEMS and active sensors are used in devices related to pressure, tire pressure monitoring systems (TPMS), chemicals, inertia, magnetism, ultrasound, imaging, radar, and Light Detection and Ranging/Laser Imaging Detection and Ranging (LiDAR)[7]. To support both the development of a mobile society and protection of the global environment, car makers are actively working to develop technologies to be used in next-generation automobiles, such as self-driving cars and all-electric vehicles (EVs)[8,9]. Autonomous cars require development of imaging and detection sensors such as cameras, lasers, and LiDAR, and all-electric vehicles require development of electric current sensors and heat sensors for managing batteries. Among these, efforts are rapidly accelerating toward integrating high-value-added sensor modules, such as imaging sensors, laser, and LiDAR[10].

2. Products Using On-board MEMS Sensors

This section introduces several examples of the latest automotive technologies that utilize on-board MEMS sensors.

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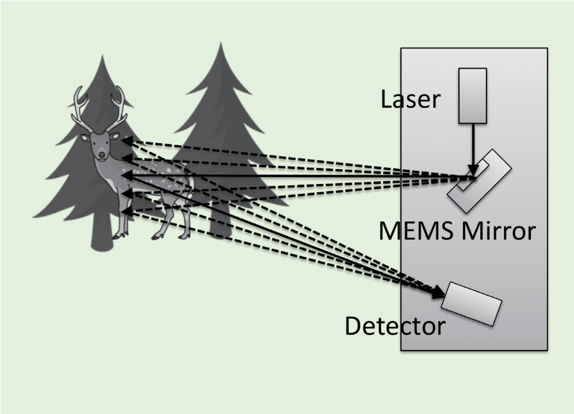

Fig. 1 Schematic drawing of LiDAR and its operation. LiDAR consists principally of a laser, a MEMS mirror, and a detector. A piezoelectric MEMS is used because of the demand for a smaller, high-performance system.

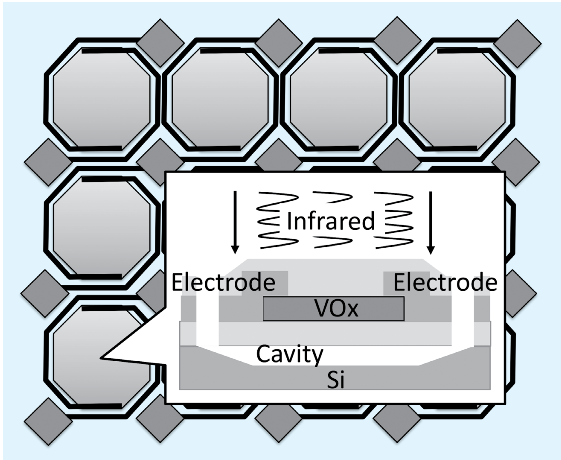

Fig. 2 Schematic drawing of an uncooled infrared bolometer array. Vanadium oxide has attracted attention because of its promise for higher performance systems.

2.1 LiDAR [11, 12]

LiDAR uses light to detect an object and measure the distance to it. The laser emits a light and measures the time it takes for the light to strike the object and bounce back, thereby measuring the distance to and the direction of the object. LiDAR can make three-dimensional (3D) observations, and can detect the angle at which the object exists and its shape far more precisely than is possible using radio waves.

As shown in Figure 1, LiDAR consists of a laser light source and MEMS mirrors that scan the laser light. Piezoelectric MEMS technology is used for the MEMS mirrors due to requirements for miniaturization and a high level of performance. Lead zirconate titanate ($PbZr_xTi_{1-x}O_3$, PZT), which is a piezoelectric material that can generate much larger vibrations than other materials when subjected to the same amount of voltage, is used as a functional film for driving.

2.2 Heads-up display [13, 14]

A heads-up display (HUD) displays information on an LCD (or similar) panel and then uses a mirror to reflect that information and project it onto the front windshield as a virtual image. An augmented reality (AR) navigation system using a HUD can improve driving safety since it can supplement the view of the traffic conditions ahead of the vehicle with (augmented) virtual information. HUDs enable drivers to obtain information necessary for safe driving from a display directly in front of them, thus helping to prevent driver distraction and reducing excessive sensory load.

Like LiDAR, these devices also use MEMS mirrors for scanning the laser light.

2.3 Intelligent headlights [15]

In terms of basic performance, intelligent headlights provide the same function as ordinary automobile headlights. However, intelligent headlights differ in that they project the light beams without blinding the drivers of oncoming vehicles and they can focus the light beams onto an obstacle (such as an animal) by working with sensors (cameras, radars, and LiDAR) to obtain external information.

Like LiDAR and heads-up displays, this technology also uses MEMS mirrors for scanning the laser light.

2.4 Night vision [16, 17]

A night vision device is an imaging device that uses electromagnetic waves outside the visible-light range, such as infrared light and microwave, to make an object in the dark visible. Infrared sensors (IR sensors) are important sensors that can make objects visible in the dark. An IR sensor uses heat detected from an object (such as an animal that constitutes a heat source) to make the object visible in the dark.

As the performance of uncooled infrared bolometer arrays (Figure 2) has now reached a level once possible only with a cooled infrared photon detector, this technology is now suitable for low-cost infrared imaging systems used in applications such as thermography, firefighting, driver night vision, security, and surveillance[18]. Although there has been a conventional technology that utilizes amorphous silicon (a-Si), more recently vanadium oxide (VOx) has been gaining attention as a new material for achieving high

Fig. 3 The “SME-200”™ is a type of multichamber sputtering system (Advanced Electronics Equipment Division).

performance. Heat changes the resistance of VOx. Because this change in resistance is large and highly linear, infrared sensors using VOx generate less noise than conventional infrared sensors using a-Si[19].

3. Technology for Forming Functional Material Films for On-board MEMS Sensors

This section describes our company’s technologies for use in the manufacture of on-board MEMS sensors, in particular a technology for forming functional oxide films, on which the authors have been working, and the performance of films made of those materials.

3.1 Formation of PZT film for piezoelectric MEMS [20,21]

As mentioned in Section 2, a piezoelectric MEMS technology is used in MEMS mirrors applied to LiDAR, etc. In order to obtain a large driving force using low driving voltage, a PZT film with a high piezoelectric coefficient and long-term reliability under harsh environments is required.

The authors used the sputtering method to form a PZT film. For the film deposition system, they used the multi-chamber sputtering system SME-200™ (Advanced Electronics Equipment Division) equipped with a dedicated sputtering module optimized for forming PZT films (Figure 3). A PZT film was formed using a PZT ceramic target (Materials Division) with the RF magnetron sputtering method. A mixture of argon (Ar) and oxygen (O_2) was used for the process gas. The thickness of the PZT film was between 0.5 and 3.0 µm in the piezoelectric MEMS application. For the substrate, a Si substrate was used in which platinum (Pt) thin film had been formed as the bottom electrode. The Pt thin film has a (111) preferred orientation, but improvements in the film-depositing process conditions for PZT, including a buffer layer, have achieved low-temperature formation at a substrate temperature of 500°C or lower as well as a c-axis or (001) preferred orientation (Figure 4 (a) and (b)). Note that PZT film made with this manufacturing method does not require a poling process for manifesting the piezoelectric characteristic.

To measure the piezoelectric characteristic, which indicates the driving performance of the PZT film, a cantilever measuring 30 mm × 3 mm was created. A laser-

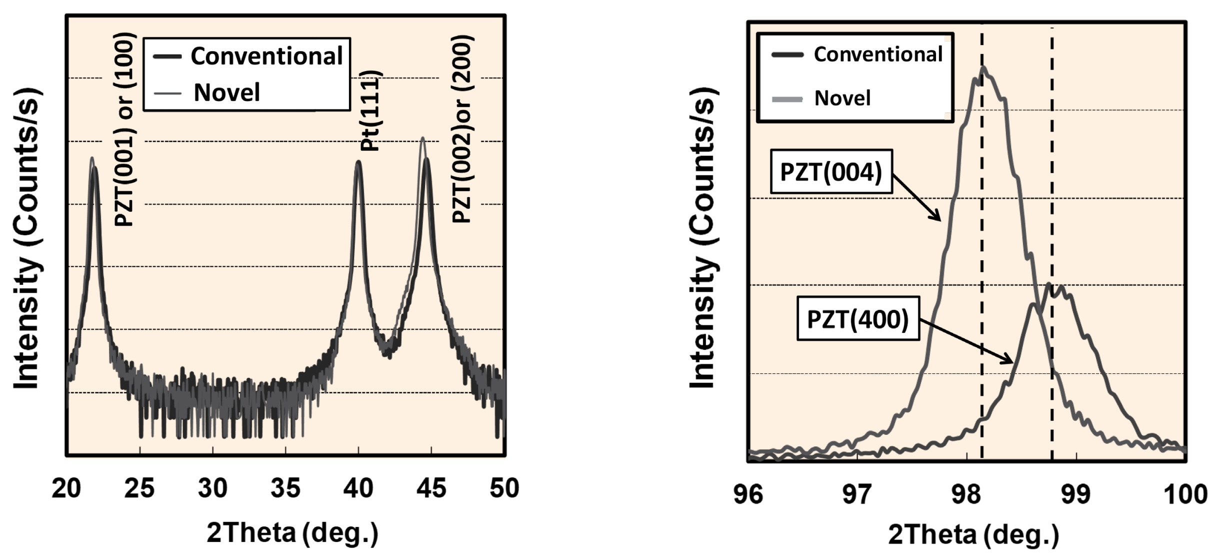

Fig. 4 XRD pattern of PZT film
(a) a-axis and c-axis oriented PZT films can be obtained onto Pt(111) film in both cases.
(b) c-axis oriented PZT can be obtained at substrate temperatures below 500°C by the novel process.

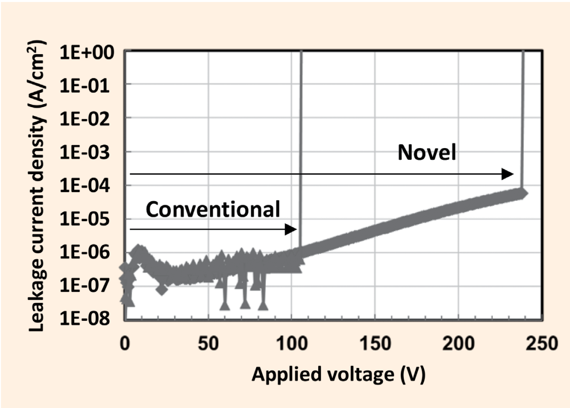

Fig. 5 Improvement of dielectric breakdown strength of PZT film

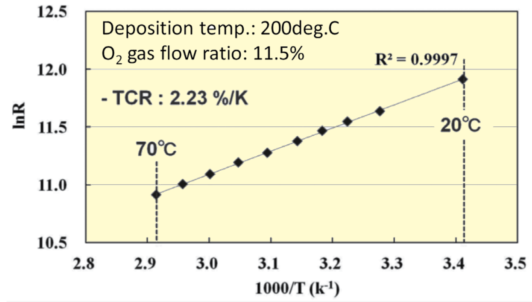

Fig. 6 TCR measurement result of VOx (thickness: 50 nm)

Doppler vibrometer and a laser interferometer were used to simultaneously observe polarization and displacement. The piezoelectric characteristic of the PZT film was confirmed by checking the displacement of the cantilever. Even using the conventional film deposition process, a relatively large piezoelectric coefficient (e_{31}) of -14.7 C/m^2 was obtained in a PZT film with a film thickness of 2.0 µm. However, with process improvements, an even greater coefficient of -15.5 C/m^2 was successfully obtained. A distinction of our company's PZT film is that it has achieved not only a high piezoelectric characteristic, but also a high dielectric breakdown voltage (V_{BD}) of more than 200 V and time-dependent dielectric breakdown (TDDB) of as long as 2 million hours, as shown in Figure 5. It has also been demonstrated that such a high-performance PZT film can be deposited at a deposition temperature of 500°C or lower.

3.2 Formation of VOx thin film for infrared sensors [22)]

VOx thin film, which possesses a large temperature coefficient of resistivity (TCR), is gaining attention as a new material for uncooled infrared sensors. In terms of characteristics, it is important to obtain not only a high TCR, but also a linear TCR in order to detect temperature changes as the current changes.

The VOx thin film was formed using a metallic vanadium target (with a 4-inch diameter) and an Ar-O_2 gas mixture with the pulsed DC magnetron reactive sputtering method. A Si substrate with a thermal oxide film was used for the substrate. The sputtering module used was equipped with a dedicated cathode with oblique incidence optimized for forming the VOx thin film and a substrate-rotating mechanism. The platform for installing the module is the same SME-200™ used for PZT in Section 3.1. The module uses a substrate heater with a high level of temperature uniformity that is capable of controlling the fluctuations in the substrate temperature distribution to 2°C or less within

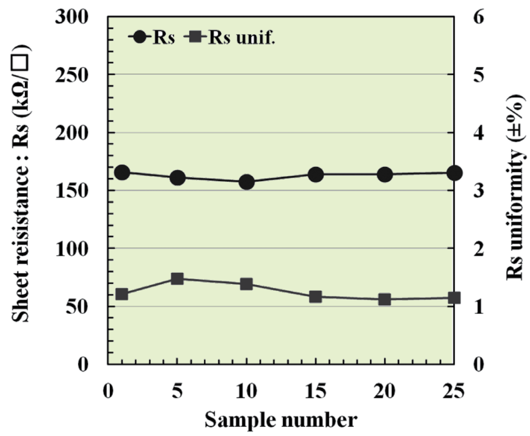

Fig. 7 Film deposition reliability test by short running with 25 wafers

a 200-mm diameter plane. This technology is necessary in order to keep the resistance value distribution of the VOx film to within ±3% of the target value; that is, to keep the fluctuations in the substrate temperature distribution to 5°C or less.

Figure 6 shows the TCR measurement results of the created VOx thin film (with a film thickness of 50 nm). The I-V characteristic was measured while heating the sample from 20°C to 70°C. The TCR value was -2.23%/K, achieving the target value (TCR < -2%/K). Within the measured temperature range, no abrupt change in the resistance value caused by a phase change was detected. Furthermore, linear regression based on the least square method resulted in a coefficient of determination R^2 of 0.9997, clearly indicating extremely excellent linearity. A film deposition stability test was also performed under the film deposition conditions that had produced the target film characteristics. Figure 7 shows the results from continuous film deposition on 25 substrates. These results indicate in-plane uniformity (measured at 49 spots) of ±2.0% or better and inter-substrate distribution (measured at 49 spots on 6 substrates) of ±3.7%, confirming that the process stably produces samples.

Our future goal is to achieve an even higher TCR while maintaining excellent linearity, in-plane uniformity, and stability.

4 Conclusion

This chapter has described MEMS sensors used in automotive applications, as well as applied technologies related to functional material films made of PZT, VOx, etc., on which the authors have been working.

To realize next-generation automobiles, such as self-driving cars and all-electric vehicles, the importance of on-board MEMS sensors and the number of sensors installed in vehicles are expected to continue growing. Besides the two materials introduced in this chapter, there are other functional materials possessing a variety of characteristics that can be expected to contribute to the realization of on-board MEMS sensors possessing new functions. In the future, the authors hope to establish technologies for depositing functional material films made of a variety of materials and to contribute to the realization of on-board MEMS sensors and next-generation automobiles.

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