Development of a pressure sensor using a piezoelectric material thin film

— Application to a combustion pressure sensor for mass-produced cars —

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In this paper, we show the process of research and development of a combustion pressure sensor using an aluminum nitride (AlN) thin film, which we developed for the first time in the world. At the time we envisaged the R&D in 2003, most sensors used a piezoelectric single crystal. The research of a combustion pressure sensor using an AlN thin film was an unexplored field, and the usefulness of an AlN thin film was not yet well recognized. However, since we started the R&D, domestic and foreign auto parts companies and universities showed interest, and we carried out joint research with a domestic company and a university toward practical use of the sensor. Consequently, we have succeeded in developing a sensor of small size, high sensitivity, and without the need of cooling. We now conduct research to resolve the problems such as stabilization of sensor signals and simplification of the sensor structure for practical use.

Keywords : Combustion pressure sensors, mass-produced cars, aluminum nitride thin films, piezoelectric type, laminate structure

1 Introduction

1.1 Necessity of the combustion pressure sensor in mass-produced cars

The improvement of fuel efficiency and measures for low pollution in automobile engines are urgent issues that must be tackled to counter the global warming caused by carbon dioxides and the elevated price of crude oil that started around 2008. Various regulations pertaining to the emissions from engines will gradually become effective around the world, such as the “Fuel Economy Standard for Heavy Duty Vehicles” from 2015 in Japan, the “Euro VI” from 2014 in Europe, and the enforcement of new gas emission standards in the United States. As measures to such regulations, the automobile companies are engaging in R&Ds for various new cars, including those with direct-injection engine, green diesel, biofuel, hybrid, electric, hydrogen, fuel cell, and others. However, at least for the next 10 to 20 years, automobiles with engines that use oil as fuel will remain the mainstream. Along with the increased performance of tires and reduced body weight, active researches are done for increased combustion efficiency, filtering technology for gas emissions, and the technologies for electronic combustion control. Various measurement technologies for pressure, temperature, flow rate, vibration, and others are necessary to develop such technology. Particularly, there are great expectations both in volume and quality of the information that can be obtained from pressure measurement, judging from the necessity, installability, precision, responsiveness, and economic feasibility of sensor development. Especially for the high-precision control of combustion in the combustion chamber, it is necessary to develop a new inter-cylindrical combustion pressure sensor with heat resistance of 400 °C or more that allows direct, high-speed measurement of the pressure in combustion chambers.[1]

1.2 Situation of the combustion pressure sensor

The piezoresistant semiconductor pressure sensor, which is the most prevalent type of pressure sensor, is small, highly sensitive, highly befitting for mass production, and dominates 83.2 % (quantity base) of the market.[2] However, its service temperature limit is about 120 °C. To increase the heat resistance, researches are being done to insert heat-insulating barrier (alumina) in the lower part of the gage, to use sapphire diaphragm, or to use chromic oxide and silicon carbide (SiC) that are highly heat resistant as the material for the gage. However, sufficient heat resistance has not been achieved.

In 1992, Toyota Motor Corporation installed a semiconductor pressure sensor for the first time in the world as the combustion pressure sensor in its mass-produced car, by maintaining the maximum temperature of the sensor element to 120 °C or lower by devising the sensor structure and layout, but this system is currently not used. From 2009, BorgWarner BERU Systems GmbH of Germany provides a glow plug with a function of the semiconductor pressure sensor incorporated into the combustion pressure sensor. Although this has been installed in some of the green diesel cars of Audi AG and Volkswagen AG, it is not yet used widely.

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On the other hand, the piezoelectric sensor that detects the charge of electric polarization of piezoelectric body is commonly used in the laboratories of universities and companies. In the piezoelectric sensor, the engine cylinder pressure received by the diaphragm is detected by the piezoelectric body. It has advantages of being small, having high response speed, and having excellent heat resistance.[1]

Crystal (SiO_2) is used as the piezoelectric material of the general-use piezoelectric combustion pressure sensor. However, since the phase transition point of crystal is 573 °C, the service temperature limit is about 350°C, and cooling is necessary for measurements at 400 °C or above. Therefore, new piezoelectric material with excellent heat resistance is being sought. As shown in Figure 1, material with high piezoelectric property tends to have low service temperature limit, and it is not easy to find an optimal piezoelectric material with high piezoelectric property and heat resistance. Around 1997, a product that used gallium phosphate ($GaPO_4$) monocrystal with theoretically estimated Curie temperature of 930 °C was realized,[1] and around 2003, the product that used langasite ($La_3Ga_5SiO_{14}$) monocrystal that does not have Curie point (phase transition point) to 1470 °C was realized.[3] Recently, a product that uses zinc oxide (ZnO) monocrystal is being proposed. While the combustion pressure sensors that use such monocrystals may have excellent heat resistance, they are generally expensive, have poor durability against mechanical impact, and have low sensor output, and therefore, are not used in mass-produced cars.

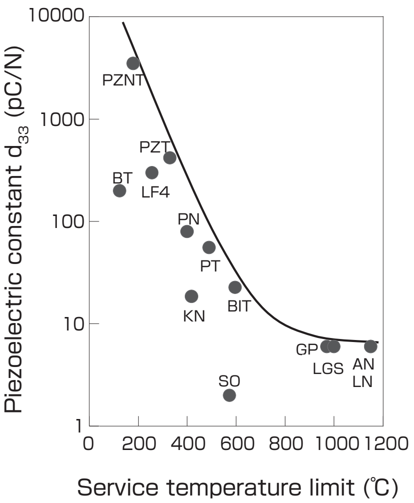

Fig. 1 Relationship between piezoelectric constant d_{33} and service temperature limit
AN: AlN, BT: $BaTiO_3$, BIT: $Bi_4Ti_3O_{12}$,
GP: $GaPO_4$, KN:$KNbO_3$,
LF4: $(K_{0.44}Na_{0.52}Li_{0.04})(Nb_{0.86}Ta_{0.10}Sb_{0.04})_3$,
LGS:$La_3Ga_5SiO_{14}$, LN:$LiNbO_3$, PN: $PbNb_2O_6$,
PT: $PbTiO_3$,
PZNT: $0.92Pb(Zn_{1/3}Nd_{2/3})O_3$-$0.08PbTiO_3$,
PZT: $Pb(Zr_{0.52}Ti_{0.48})O_3$, SO: SiO_2

As shown above, to realize a high output, low priced combustion pressure sensor that shows heat resistance at 400 °C or over and excellent durability (at least 10 years or more), completely different technological development is necessary in all aspects, including the piezoelectric material, element structure, and sensor form.

With such a background, the authors simultaneously engaged in research for heat resistance, durability, high output, and low price of the combustion pressure sensor. With the objective of developing a combustion pressure sensor for mass-produced cars, we started to engage fully in the research with support from the AIST High-tech Manufacturing Project in 2003. This research was not a revision or improvement of an already existing combustion pressure sensor, but was a R&D of the world's first combustion pressure sensor in that it employs a structure in which the sensor elements were laminated to achieve high output, by using thin films as the detecting material rather than using the conventional monocrystal, to realize durability and low cost.

2 Scenario for developing the combustion pressure sensor for mass-produced cars

Figure 2 shows the scheme of the integrated scenario for the development of a combustion pressure sensor for mass-produced cars set as the final R&D goal and the necessary elementary technologies.

We set the following five points as topics to focus on in the first stage of R&D, with the issues (heat resistance, durability, high output, low cost) confronting the conventional combustion pressure sensors in mind.

- Development of the technology to fabricate piezoelectric thin films
- Development of the technology to evaluate the electric

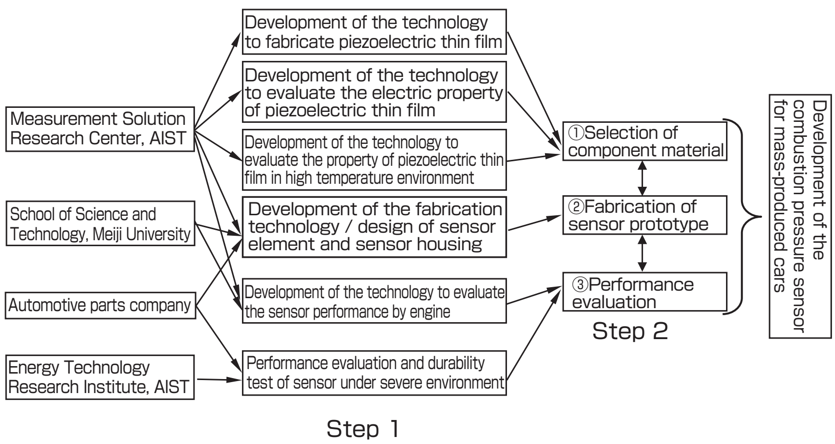

Fig. 2 Elemental technologies for development of combustion pressure sensors for mass-produced cars and scenario for integration

property of piezoelectric thin films
- Development of the technology to evaluate the property of piezoelectric thin films in high temperature environment
- Design of sensor element and sensor housing
- Development of the fabrication technology
- Development of the technology to evaluate the performance of the sensor by engine

The second stage is currently in progress, and the selection of the component materials for the combustion pressure sensor for mass-produced cars by the integration of these elemental technologies, prototype sensor fabrication, and performance evaluation tests are being done. In the above scenario, we hope to contribute to the development of control technology for the next-generation high-performance engine.

At the beginning of the R&D, it was assumed that the development of a combustion pressure sensor for mass-produced cars would progress by replacing the piezoelectric parts, which is the detecting material of the commercial combustion pressure sensor, if the piezoelectric property of the AlN thin film could be clarified. However, when the actual joint research was done, the automotive parts company did not have much experience in studying the piezoelectric combustion pressure sensor. Therefore as the research progressed from the development of the technology to fabricate the piezoelectric thin films to the development of the technology to evaluate the electric property of piezoelectric thin films, the development of the technologies to evaluate the property of piezoelectric thin films in high temperature, to design and fabricate the sensor element and housing, and to evaluate the sensor performance with an engine were conducted concurrently, with the cooperation of the automotive parts company and the university.

In the performance evaluation test, the commercial piezoelectric combustion pressure sensor was set as the evaluation standard. Since the output (sensitivity) of the piezoelectric combustion pressure sensor is largely affected by the form of the sensor, the evaluation was done based on how close the product approached the response waveform of the commercial sensor, rather than directly comparing the sensor output values.

Since the sensor output in a certain set range is necessary for installment in mass-produced cars, the R&D was done considering the structure that allowed adjustment of the sensor output after the performance evaluation. At the same time, the practical issues of the prototype sensor that were not considered during the initial performance tests were investigated, and revisions and improvements were conducted to create the combustion pressure sensor that was as close to the completed product as possible.

The above R&D was conducted jointly by AIST, the automotive parts company, and Meiji University. The individual specialties and experiences were gathered for the technologies for thin film fabrication, analysis of the property and phenomenon in high temperature environment, dynamic analysis, sensor design, and others. The team from the Measurement Solution Research Center, AIST was in charge of the development of technologies to fabricate the piezoelectric thin films, to evaluate the electric property of piezoelectric thin films, to evaluate the property of piezoelectric thin films in high temperature, to design and fabricate the sensor element and housing, and to evaluate the sensor performance with an engine. The Meiji University team worked on the development of technologies to design and fabricate the sensor element and housing, and to evaluate the sensor performance with an engine. The automotive parts company team worked on the development of technologies to design and fabricate the sensor element and housing from the standpoint of auto-parts manufacturing, and conducted the performance and durability tests of the sensors in severe environments. The team from the Energy Technology Research Institute, AIST was also in charge of the performance and durability tests of the sensors in severe environments.

Table 1. Comparison of major characteristics of piezoelectric material

	AlN	SiO_2	$Pb(Zr,Ti)O_3$	$GaPO_4$	$LiNbO_3$	$La_3Ga_3SiO_{14}$
Piezoelectric constant d_{33} (pC/N)	6	2	250	6	35	6
Service temperature limit (℃)	1200	350	250	920	1200	1000
Ease of fabricating the thin film	Excellent	Impossible	Possible	Impossible	Good	Impossible

In this R&D, a place for sharing the information and exchanging opinions were set for the teams and members. Mutual attendances to the performance tests and application tests were arranged, to take advantage of the joint project as much as possible.

The following section of the paper is the outline of the development of the core elemental technology and the performance evaluation of the prototypes, in the R&D of the combustion pressure sensor.

3 Fabrication and evaluation of the piezoelectric thin films

3.1 Selection of the piezoelectric material and thin film fabrication

The authors' team selected aluminum nitride (AlN) as the detection material for the following reasons: 1) shows highest service temperature limit at 1200 °C among the piezoelectric materials, 2) does not contain hazardous elements such as heavy metals, 3) shows three times the piezoelectric characteristic of crystal, and 4) has high elasticity coefficient (Young's modulus: 314 GPa) and piezoelectric linearity is maintained at high pressure.[4] By selecting AlN as the detecting material, the issue of heat resistance was easily cleared.

We considered using the thin film instead of monocrystal as the structure of the detecting material because, if the charge generated by the piezoelectric material is used as the output signal of the sensor, the sensor output will not be dependent on the thickness of the piezoelectric material. By using the thin film, the disadvantage of the fragility of the monocrystal can be overcome, and high durability against mechanical impact can be obtained. Moreover, it will be possible to use the semiconductor process that is readily mass-producible, and low cost can be achieved. Compared to other hopeful piezoelectric materials, there are less number of elements in AlN, and therefore it can be readily made into thin films. Hence, the authors' research team employed the AlN thin film as the detecting material of the combustion pressure sensor for the first time in the world, and embarked on the development of technology to fabricate the AlN thin film.

To investigate whether the AlN thin film showed the piezoelectric response as reported, an AlN thin film was fabricated on a silicon monocrystal substrate using the reactive sputtering method, and the piezoelectric responsiveness of AlN thin film was studied. The piezoelectric response of the fabricated AlN thin film showed good linearity in the pressure range of 0.1~1.6 MPa, and also showed good frequency property in the 0.1~100 Hz range. Therefore, it was confirmed to be an adequate candidate of the sensor material (2005).[5] The analysis of the basic property was conducted by the electric model of an AlN thin film, and good linearity similar to the combustion pressure of the engine was obtained in the 0.4~8.0 MPa range. Since the measured values and the electric model matched, it was shown that the AlN thin film could be used as the detecting material for the combustion pressure sensor (2005).[6] The electric resistance of AlN thin films decreases dramatically as the temperature increases, according to the Arrhenius equation. When the resistance decreases, the charge generated in the piezoelectric material diffuses before it can be detected by the measurement system so it cannot be measured. Therefore, we studied the volume resistivity of the AlN thin film and the temperature dependency of relative permittivity. Figure 3 shows the results. The volume resistivity of the AlN thin film was 10^6 Ωcm or more at 851 °C, and the permittivity increased only slightly. Therefore, it was found that measurement was possible for the AlN thin film at 800 °C or above (2006).[7]

However, since the monocrystal silicon substrate was used, the sensor element was weak against mechanical impact, and it was necessary to develop a sensor element with good

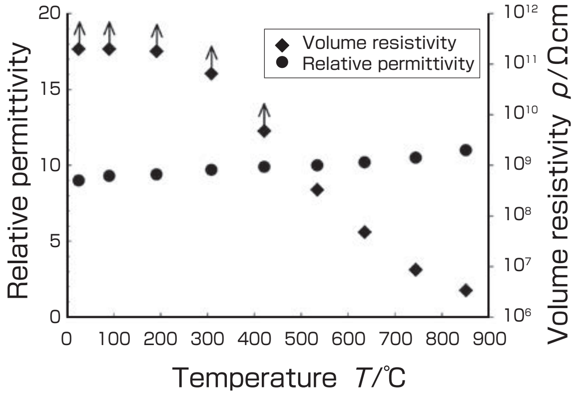

Fig. 3 Temperature dependence of the relative permittivity and volume resistivity of AlN thin film

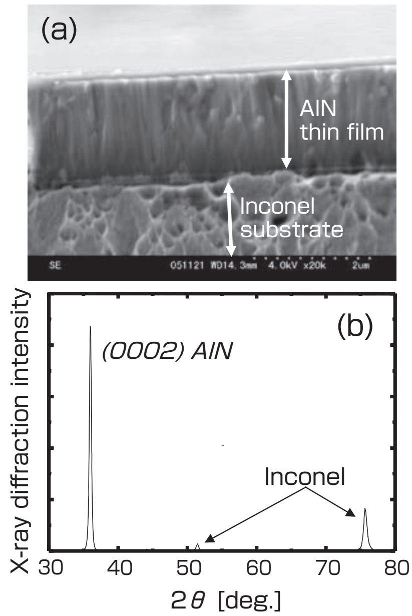

Fig. 4 (a) Cross sectional SEM photograph and (b) XRD pattern of AlN thin film fabricated on Inconel substrate

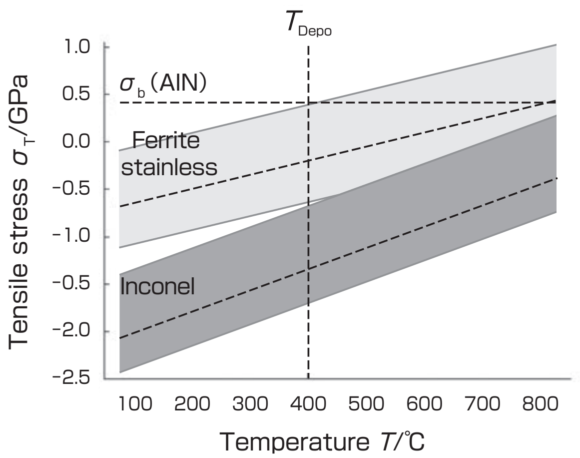

Fig. 5 Temperature dependence of internal stress of AlN thin film formed on various substrate materials

durability. The authors fabricated the AlN thin film on a metal substrate to increase the durability against mechanical impact. For the metal substrate material, we selected Inconel, a nickel superalloy with excellent heat resistance. The AlN thin film was fabricated on the multicrystal Inconel substrate by the sputtering method, and we successfully fabricated the thin film with crystalline orientation (2006).[8] Figure 4(a) shows the SEM photograph of the cross section of the AlN thin film fabricated on the Inconel substrate. The XRD pattern of this thin film is shown in Fig. 4(b). From the cross section of the AlN thin film, it was observed that it was composed of fine crystal particles with fibrous structure, in which the thin film grew vertically against the substrate surface. Although the Inconel substrate is multicrystalline, the AlN thin film showed only the diffraction peak of 0002 face of wurtzite type AlN, and presented the c-axis orientation. The piezoelectric constant (d_{33}) measured using the piezometer was 2.4 pC/N, which was about half the value of monocrystal AlN, but we were able to fabricate the AlN thin film with piezoelectric property on the Inconel substrate.

Figure 5 shows the bending strength σ_b(AlN) and the temperature dependency of in-plane stress that occurs in the AlN thin film fabricated on the ferrite stainless and Inconel substrates.With both substrates, it was found that the stress distribution range was wide, and a clear difference was seen between the two substrates. Both were fabricated at 400 °C, but after fabrication, about twice the compression stress was working on the Inconel material compared to the stainless one. Also, since the coefficient of thermal expansion of AlN was smaller than those of the two alloy substrates, the tensile stress increased by heating. As a result, stress surpassing the rupture strength of the AlN thin film might occur locally when 400 °C was surpassed in the stainless sample. On the other hand, rupture strength of the AlN thin film was not surpassed even at 800 °C in the case of the Inconel sample. From these results, it was found that the choice of the metal substrate material is important to prevent the rupture of the AlN thin film.

3.2 Evaluation of the electric property in high temperature environment

The piezoelectric property of the AlN thin film fabricated on the Inconel substrate was studied in a high temperature environment. Figure 6(a) shows the amplitude change of the charge generated by the AlN thin film when the oscillation amplitude was varied by applying pressure at a constant frequency. The AlN thin film showed linearity at a high pressure range of 10~300 MPa. It was found that the AlN thin film had sufficient pressure resistance as a combustion pressure sensor, since the maximum pressure inside the combustion chamber of a standard car is several tens of MPa.

Figure 6(b) shows the frequency response of the AlN thin film at sine wave oscillation amplitude of 300 MPa for the applied pressure. Here, the gain of the AlN thin film is standardized as output value Hz. The gain was mostly flat at high frequency range (3~30 Hz) and the phase shift was small. It was found that the AlN thin film had sufficient

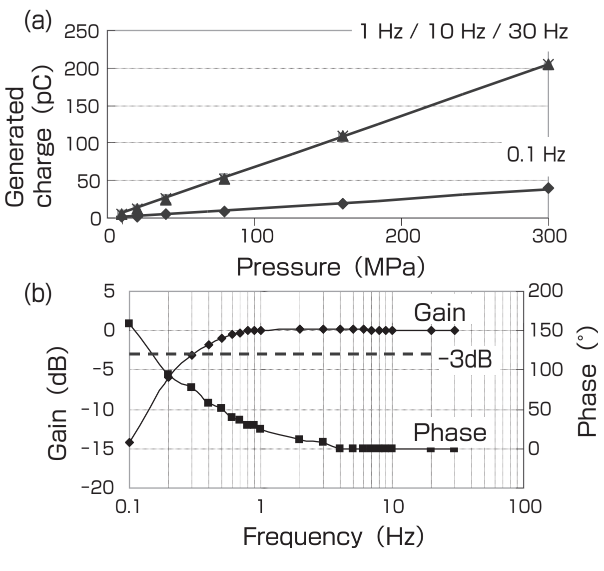

Fig. 6 (a) Pressure dependence of generated charge of AlN element for frequency between 0.1~30 Hz, and (b) frequency response of gain and phase of AlN element against pressure change of 150 MPa

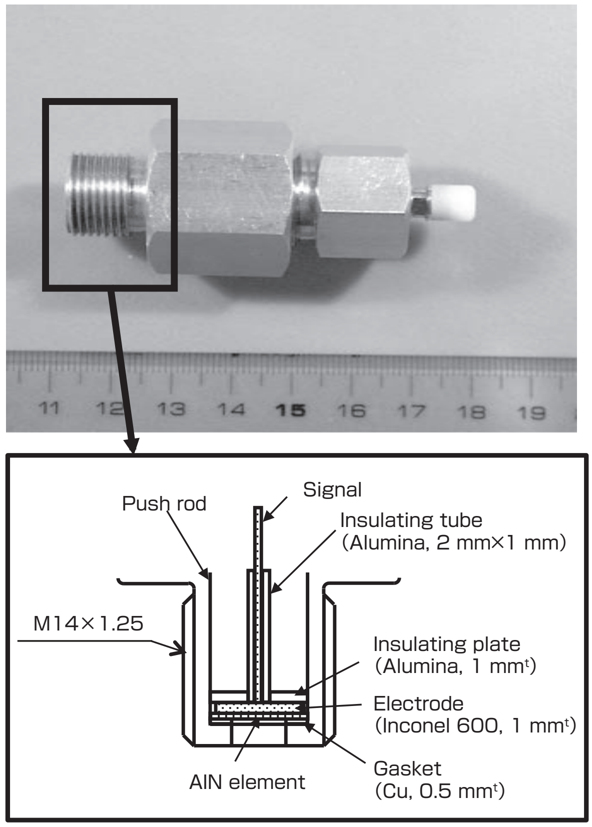

Fig. 7 Appearance of AlN sensor and schematic diagram of interior structure

frequency responsiveness, since the revolution of the car engine is several thousand rpm (several ten Hz). When the measurements were done in a high temperature environment, it was confirmed that the piezoelectric response of the AlN thin film did not change at all for 54 h at 450 °C (2006).[9]

4 Fabrication of the sensor prototype and its evaluation

4.1 Performance evaluation with an engine

Since we obtained a prospect of using the AlN thin film element, we fabricated a prototype of the combustion pressure sensor (2007).[10] Figure 7 shows a photograph of the combustion pressure sensor fabricated with the AlN thin film and the schematic diagram of the sensor structure. The pressure receiving part of the sensor had a simple structure where the AlN thin film element was held with a discoid internal electrode to receive the charge with the signal wire. An alumina plate and an alumina tube were used to insulate it from the housing. To investigate the combustion pressure response property of the AlN sensor, single cylinder two-cycle engine (HONDA LEAD 90, HF05) was used. As shown in Fig. 8, the sensor was installed near the apex of the cylinder head to measure the pressure of the combustion chamber. To conduct performance comparison, the combustion pressure sensor (No. 6001) of Kistler Corporation was used because this was most widely used in engine research. The output of the AlN sensor when the engine revolution was set to about 4000 rpm without load was compared to the commercial sensor. The result is shown in Fig. 9. Since the generated charge of the commercial sensor was 140~160 pC, the pressure inside the combustion chamber was 1.1~1.2 MPa. There was almost no external noise in the output wave of the AlN sensor, and almost the same waveform was observed as that of the commercial sensor.

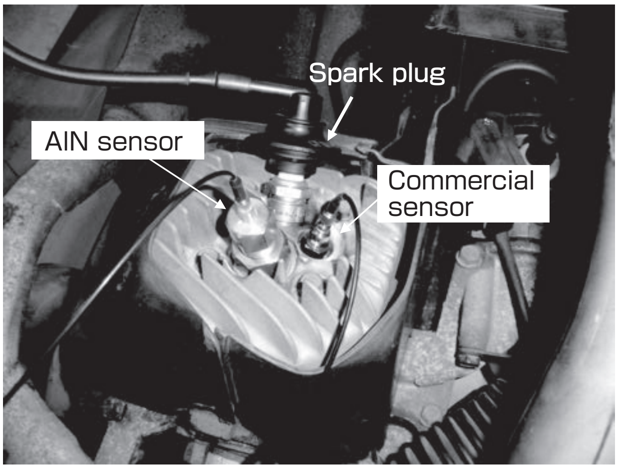

Fig. 8 Attachment of sensor to two-cycle engine

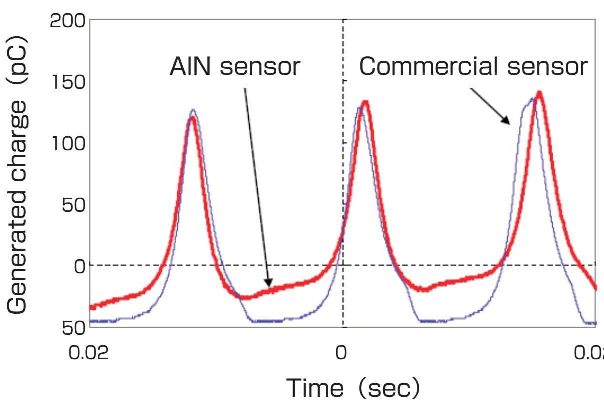

Fig. 9 Output waveform of sensor during operation of two-stroke engine
Engine revolution: about 4000 rpm

To evaluate the durability of the AlN sensor, the change of sensor output when the engine was repeatedly run at about 2000 rpm for 20 min, cooled, and then run for 20 min again is shown in Fig. 10. Since the revolution of the engine could not be kept constant accurately, there were variations in the output value for each measurement, but a fairly constant output was obtained. There was almost no decrease in output after a total of 40 hours, and stable operation continued.

The initial objective was to confirm whether the measurement of combustion pressure was possible in a real engine, and to obtain the output waveform close to the commercial sensor. We were able to obtain almost similar response waveform as the commercial sensor and the initial objective was achieved.

The commercial sensor is made by finely processing fragile crystal monocrystals and then combining the monocrystal pieces. Since it has a complex structure where the small crystal plates are cut out by orienting the crystal axes and then combining them, high cost and technique are required to fabricate the element. In fact, the commercial sensor used for comparison cost several hundred thousand yen. On the other hand, the AlN sensor developed by the authors has a simple structure where the AlN thin plate fabricated on the metal plate is held with electrodes, and we aim for the price of 10,000 yen or less, as the sensor for mass-produced cars.

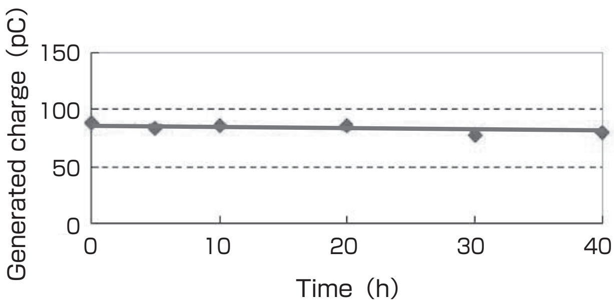

Fig. 10 Dependence of AlN sensor output on engine run time
Intermittent run at engine revolution 2000 rpm × 20 min

4.2 Downscaling for mounting in automobiles

As the research progressed, we faced the problem that the charge amp that were used in the lab could not be installed in mass-produced cars due to difference in power source, severe use condition, price, and others. Therefore, an amp that was already installed in the car for a different purpose was used, but the sensor output several times higher was necessary to use that amp. The recent high-performance engines have become increasingly complex in structure due to the employment of the high-pressure fuel injection system and increased number of valves, and there was no space to mount the combustion pressure sensor with a large housing as used in the above experiment. Therefore, we had to downscale the housing. In case of the piezoelectric material, since the generated charge was proportional to the pressure receiving surface area, it was necessary to increase the pressure receiving surface to increase the sensor output. However, when the pressure receiving surface was increased, the size of the sensor element increased, and this in turn, meant it could not be installed on the engine.

The authors considered the ways to decrease the volume while increasing the sensor output, and devised a way to decrease the volume by increasing the surface area of the sensor element, by stacking the sensor element vertically. However, to realize such laminated structure, the lamination had to be done without having the thin film surface or the substrate contacting the housing. Therefore, the authors devised the element structure shown in Fig. 11.[11] In this structure, a hole was punched in the center of the circular metal substrate, AlN was formed on the entire surface except that part, signal wires were passed through the central hole, and the elements where the AlN surface was covered with copper foil were laminated. Since AlN is an insulator, if the signal wire is insulated from the housing, the substrate side of the AlN thin film and the surface will not come in contact. The commercial sensor and the AlN sensor are compared in Fig. 12. The exterior diameter of the AlN sensor was 4.6 mm, and the thickness of the sensor element was 0.2 mm and AlN was formed at about 3 μm thickness on both sides of the metal substrate. This was wrapped with a copper foil electrode of 10 μm to fabricate the element shown in Fig. 11, and was

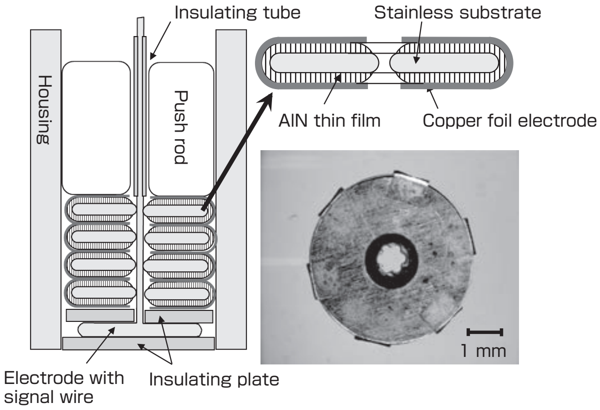

Fig. 11 Diagram and photograph of laminated structure of AlN thin film sensor element

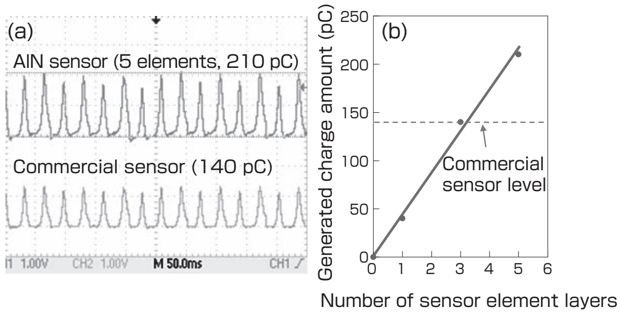

Fig. 13 (a) Response waveform of AlN sensor, and (b) dependence of generated charge amount on number of sensor elements

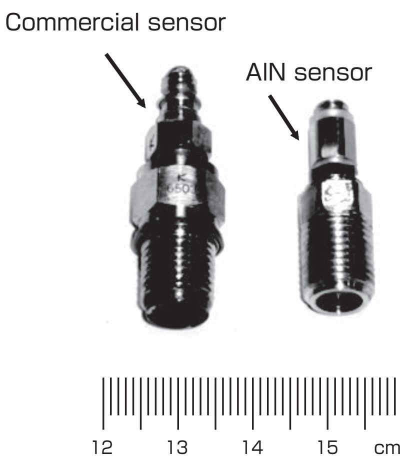

Fig. 12 Appearance of fabricated AlN sensor prototype

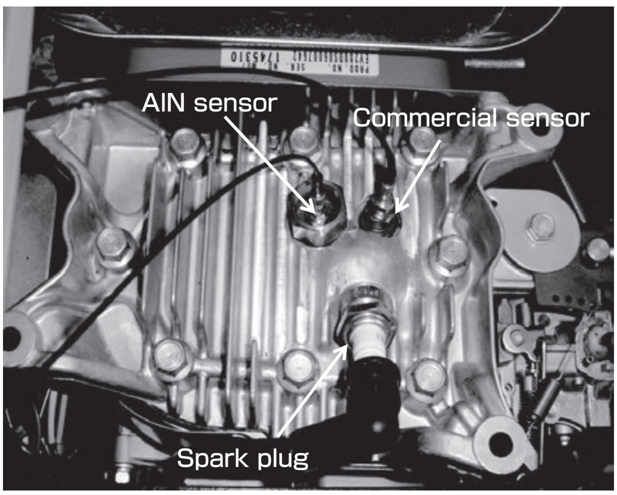

Fig. 14 Appearance of four-cycle engine with sensors attached

assembled as shown in Fig. 12. The AlN sensor housing was a screw of external diameter of 10 mm and 1 mm pitch, and this was attached to the engine. The appearance was similar to the commercial sensor (Kistler 6001) installed using the engine mounting adapter.

The AlN sensor and the commercial sensor were installed on an engine, and the combustion pressures were measured. The output waveforms of sensors with one, three, and five layers of AlN elements were measured. The output waveform of the sensor with five layers is shown in Fig. 13(a). A waveform similar to the commercial sensor was obtained, and the generated charge was higher. Figure 13(b) shows the dependency of the generated charge on the number of layers. The output of the element was 40 pC with one layer, 140 pC with three layers, and 210 pC with five layers. The generated charge increased linearly as the layers increased, and about the same output was obtained with three layers as the commercial layer. It was determined that the minimum sensitivity as an actual sensor onboard a car was satisfactory if the generated charge was the same level as the commercial sensor. Using this housing, a maximum of 15 layers of the element with thickness of 0.2 mm can be installed, and the output of 4.5 times higher than the commercial sensor can be obtained when 15 layers are used.

The two-cycle engines are used in motorcycles and scooters since there are problems of fuel efficiency and exhaust gas. Four-cycle engines are used in mass-produced cars, and evaluation using the commercial four-cycle engine (Robin Engine EY28DS manufactured by Fuji Heavy Industries Ltd.) was conducted. As shown in Fig. 14, the AlN sensor was installed on the cylinder head valve side of the engine using an adapter, the commercial sensor was attached directly on the right side, and the measurements were taken. For this AlN sensor, three layers of the AlN thin film with increased sensitivity achieved by adding Sc was used.[12] Figure 15 shows the outlet waveforms of the AlN sensor and the commercial sensor. The output of the commercial sensor was 52 pC and the output of the AlN sensor was 151 pC, three times the output of the commercial sensor. If the maximum of 15 elements were used, 15 times the output of the commercial sensor can be expected. The slight pressure change at exhaust that could be seen as broad peaks in the commercial sensor could be observed as clear peaks in the AlN sensor. From these results, it can be expected that the AlN sensor may greatly exceed the performance of commercial sensors, and will perform as a practical combustion pressure sensor.

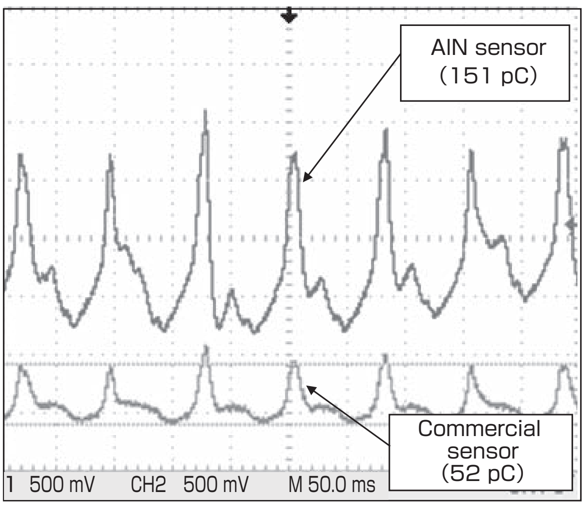

Fig. 15 Response waveform of AlN sensor in four-cycle engine

5 Conclusion

In this paper, the history of the R&D of combustion pressure sensors was described, where the authors used the thin film piezoelectric material for the first time in the world. In the field of combustion pressure sensors before the ideation of this R&D (before 2003), the thin film piezoelectric material was an unknown field and its usefulness was not recognized. However, since the start of this research, the automotive parts companies and universities of Japan and overseas became interested, and joint research was done with the Japanese automotive parts company and Meiji University. Before this thin film combustion pressure sensor can be installed in the mass-produced cars, there are still several more issues that must be solved such as the demonstration test of environment resistance and durability, stabilization of sensor signals, achievement of high output, simplification of sensor structure, and others. It is still in the “valley of death.” However, through the cooperation with various people, the issues are being overcome one at a time, and we have been able to move forward one step at a time. With the actual use and diffusion of this thin film sensor, the exhaust gas volume of the cars that are running around the world may decrease dramatically, hence it will contribute greatly to the environment and energy fields. Also, the potential is high for application to the engines of vessels, special vehicles, and generators, and the ripple effect can be infinite.

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Discussions with Reviewers

1 Installation of combustion pressure sensor to the commercial automobile

Question (Masahiro Okaji, Chino Corporation; Shuji Abe, AIST)

(Subchapter 1.2) As an example of the installation of the combustion pressure sensor to the engine of mass-produced cars, you give the Toyota Motor's piezoresistant sensor, but you also write, "This system is currently not used." What was the reason that it was discontinued? Do you mean that this is the only case in the past, and there is no other example where it was installed in mass-produced cars (including foreign auto makers)?

Answer (Morito Akiyama)

I do not know the exact reason why Toyota Motor's piezoresistant sensor was discontinued. After careful survey, I did find that the piezoresistant glow plug type combustion pressure sensor that was jointly developed by BorgWarner BERU Systems GmbH, a German spark plug company, and Texas Instruments Inc. of the United States had been installed in the green diesel cars of Audi AG and Volkswagen AG from 2009, and these cars are sold in Europe and North America. I revised part of the text and included this point.

2 Disadvantage of the piezoelectric sensor

Question (Masahiro Okaji and Shuji Abe)

(Subchapter 1.2) You wrote that the piezoelectric sensor "has disadvantages such as that absolute pressure measurements cannot be taken." Does this pose any practical problem?

Answer (Morito Akiyama)

Since the combustion pressure of an automobile engine changes rapidly, it is possible to take measurements with a piezoelectric sensor. However, to prevent misunderstanding, I eliminated the expression "has disadvantages such as that absolute pressure measurements cannot be taken," as this is an irrelevant comment.

3 Reason for continuing the research at AIST

Question (Masahiro Okaji and Shuji Abe)

(Chapter 5) You write, "…There are still several more issues that must be solved…. It is still in the 'valley of death.'" However, it seems that the demonstration test for durability, for example, entered the phase where it should be carried on by private companies. Is it still in the phase where R&Ds must be continued at AIST and universities? Since I get the impression that the research stage at AIST has passed, I think you should clearly state the reason why AIST should still continue the research.

Answer (Morito Akiyama)

The demonstration test for durability and others have entered the phase that should be done by private companies. However, to increase the integrity of the sensor, there are points that must be improved such as the stabilization of sensor signals and achievement of high output, as well as simplification of the sensor structure. I added this comment at the end of chapter 5 as projects that must be undertaken by AIST.

4 Comparison of the studied sensor and commercial sensor

Question (Masahiro Okaji)

(Subchapter 4.2) As shown in Fig. 13, the discussion progresses by comparing the studied sensor and the commercial sensor. If the generated charge is at the same level as the commercial sensor, will it satisfy the condition for the car-mounted sensor?

Answer (Morito Akiyama)

I added the sentence, "It was determined that the minimum sensitivity as an actual sensor onboard a car was satisfactory if the generated charge was the same level as the commercial sensor." to subchapter 4.2.