Trends in Hitachi's MEMS Sensors for Automobiles

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OVERVIEW: Computerized and electronic control technologies for automotive systems such as engine powertrain control, vehicle stability control, and brake control have been evolving year after year, making the establishment of the sensing technologies used to acquire the various types of information necessary to control these systems indispensable. MEMS is a core technology that supports this, and a wide variety of different MEMS sensors are currently being used on board automobiles. Ever since Hitachi first commercialized semiconductor pressure sensors in 1980, Hitachi has been working to apply MEMS technology to devices such as accelerometers, airflow sensors, and so on. Furthermore, in 2009, Hitachi developed a combined sensor that measures automobile acceleration along two axes (back and forth plus side to side) as well as rotation (angular rate), and is working to gradually begin applying this sensor to its vehicle electrical stability control system starting in 2011, as this system will become mandatory in North America and Europe.

INTRODUCTION

SINCE it began working on the development of semiconductor pressure sensors using bulk MEMS (microelectromechanical systems) fabrication technology for fabricating three-dimensional silicon substrates in 1970, Hitachi has been developing technologies such as MEMS fabrication technology and the integration of MEMS and signal processing circuits, while working to commercialize these technologies. At present, Hitachi is also focusing on the creation

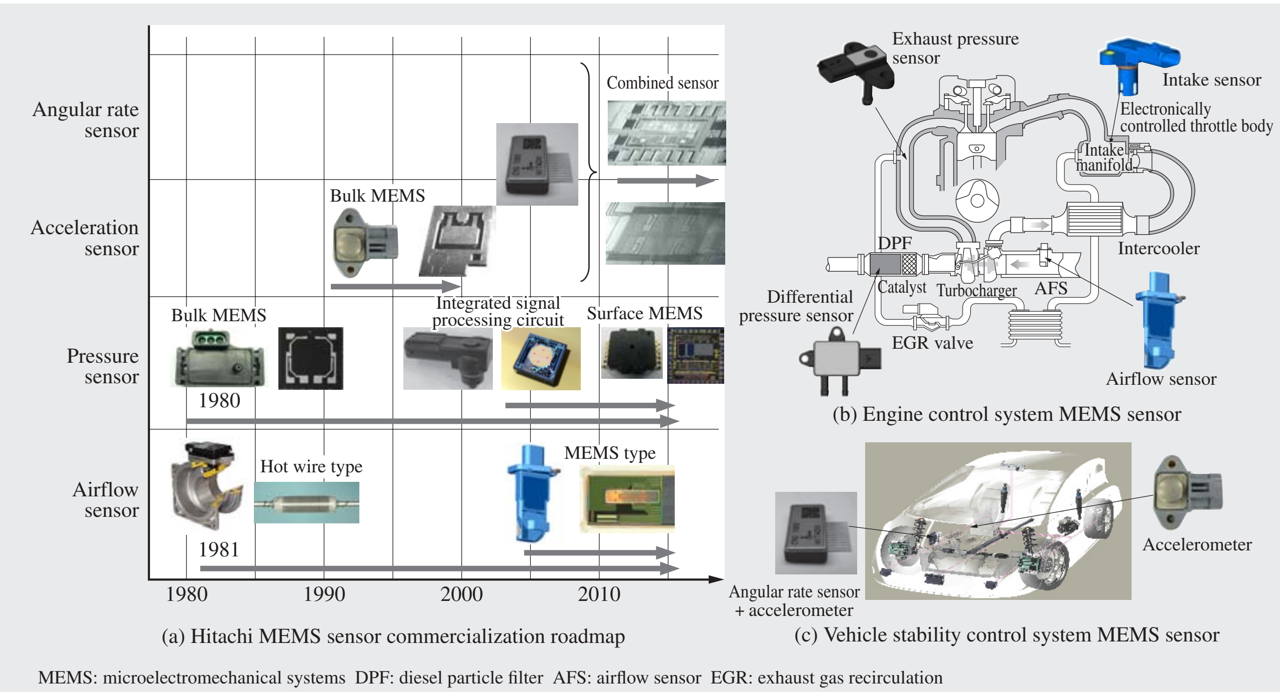

Fig. 1—Hitachi MEMS Sensor Roadmap and Positions of Various Sensors in Vehicle.
The history of Hitachi's development of sensors applying MEMS technology, as well as the positions of on-board sensors used for automobile control are shown. The development and adoption of MEMS technology has expanded the range of applications for automobile sensors.

of combined MEMS sensors with a higher degree of complexity (see Fig. 1).

This document discusses Hitachi's development trends in MEMS sensors for automobiles, including MEMS airflow sensors for measuring airflow, single-chip pressure sensors integrating MEMS with signal processing circuits, and two-axis acceleration and one-axis angular rate measurement through combined sensor for vehicle control.

MEMS AIRFLOW SENSORS

Regulations requiring the reduction of automobile emissions for the purpose of conserving the global environment have been growing stricter year after year. In order to comply with these strict emission regulations, high-precision air-fuel ratio control is essential, and there is a need for highly precise and reliable measurements of intake air mass over a wide range of measurement.

In response to the strengthened regulations of emissions and the need for improved fuel efficiency in recent years, fuel has been directly injected into cylinders via DI (direct injection), diesel engines have been used, cylinder halting functions have been adopted for improved fuel efficiency, and so on. This results in a large pressure pulsating flow in the air intake, and the number of engines whereby a reverse flow of intake air back into the intake side occurs has increased. As this pulsating flow fluctuates rapidly, it is necessary to accurately measure the amount of air flowing into the cylinder, but with traditional hot wire airflow sensors, the direction of airflow cannot be precisely detected. It is for this reason that the MEMS airflow sensor was developed, in order to accurately measure the intake air mass of reverse flows and rapidly pulsating flows. This new sensor was commercialized in 2005 (see Fig. 2).[1]

The MEMS airflow sensor is formed with a diaphragm structure etched on the reverse side of a silicon substrate, with a heater resistor on the diaphragm and two temperature sensor resistors located near the heater resistor. The heater is supplied with electric current, controlling the heating at a constant temperature, using the air heat transfer amount distributed among both nearby temperature sensors and depending on the airflow speed. The heater resistor and temperature sensor resistors are fabricated on a diagram that is extremely thin at several micrometers, which makes it possible to achieve high-speed responses to low levels of heat capacity over several milliseconds.

The principle of airflow detection is shown in Fig. 3. The temperature distribution on the silicon diaphragm when there is no airflow is symmetrically arranged around the heater at the center. When there is airflow, the temperature of the downstream side temperature sensor increases just ΔT, depending on the direction and flow rate. When a reverse flow occurs, the temperature of the upstream side's temperature sensor increases ΔT. The temperature differential ΔT is detected from the resistance differential of the two temperature sensors formed on both sides near the heater, which makes it possible to determine the flow rate and flow direction. This temperature differential

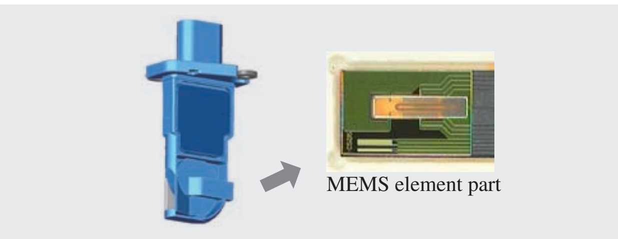

Fig. 2—MEMS Airflow Sensor Appearance.
The adoption of MEMS elements also enables high-speed responsiveness.

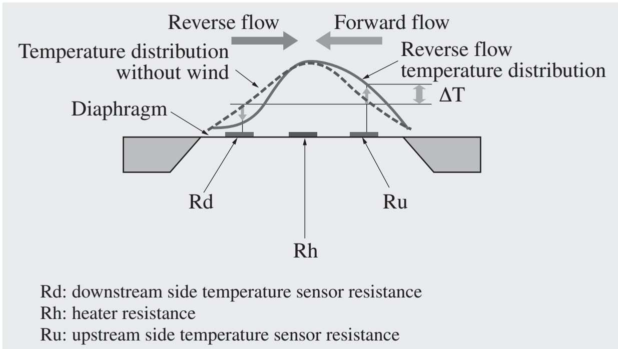

Fig. 3—MEMS Airflow Sensor Detection Principle.
The placement of detection elements formed on a diaphragm enables the measurement of forward and reverse flows.

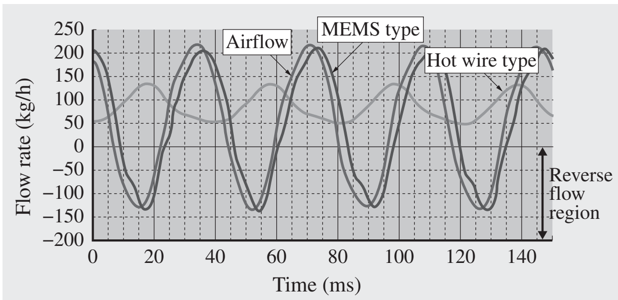

Fig. 4—Hot Wire and MEMS Sensor Flow Characteristics.
The MEMS sensor's characteristics with respect to airflow allow for the accurate measurement of flow rate in the reverse flow region as well.

ΔT is converted to an output characteristics signal corresponding to the flow rate, based on a combination of the constant temperature differential bridge circuit and the temperature differential detection circuit. The MEMS element is rapidly responsive and has a reverse flow detection function that also enables reverse flow error compensation in the pulsating flow. In addition, since the sensor is manufactured using a semiconductor process, this offers the benefits of both miniaturization and easy mass production.

The characteristics of the MEMS airflow sensor's reverse flow region are shown in Fig. 4. The conditions for detecting a reverse flow also allow for a more accurate detection of the actual air pulse than what is possible with the traditional.

At present, in addition to the airflow, the EGR (exhaust gas recirculation) flow rate is also measured, and multiple items of sensor information from sensors such as a pressure sensor and a throttle position sensor are being used in the development of precise air-fuel ratio control technology as well.

In the future, in order to achieve these goals, in addition to the miniaturization of sensors and the smart processing of digital signals, further improvements in precision and multifunctionality will be continuously developed as well.

SINGLE-CHIP PRESSURE SENSORS WITH INTEGRATED MEMS AND SIGNAL PROCESSING CIRCUITS

Pressure sensors for automobiles have been used to measure variables such as engine control, fuel pressure, and brake oil pressure. Hitachi led the world by starting the production of semiconductor pressure sensors in 1980. This sensor has a piezoresistor formed on a silicon diaphragm, and can use the deformation of the diaphragm caused by pressure to measure variations in resistance.[(2)]

In recent years, in addition to the aforementioned measurements, the market has been growing for the TPMS (tire pressure monitoring system) and collision detection systems. TPMS has been becoming mandatory in stages in North America starting in 2005 due to the enactment of the TREAD (Transportation Recall Enhancement, Accountability, and Documentation) Act of 2003, and has been installed in every new vehicle sold in the USA since 2008. When it comes to collision detection, the USA revised side collision standards in 2008, increasing the importance of curtains and side airbags. When compared with the detection of collisions from shock, the detection of pressure inside doors has shown to be superior in terms of both accuracy and speed, and so pressure sensors are increasingly being adopted.

Tire pressure sensors measure between 0.3 and 1 MPa, and side collision sensors measure around 0.1 MPa of pressure. Both types of sensors need to be miniaturized, highly sensitive, and low in power consumption. To meet these needs, a sensor was developed integrating LSI (large-scale integration) and the MEMS diaphragm into a single-chip pressure sensor.

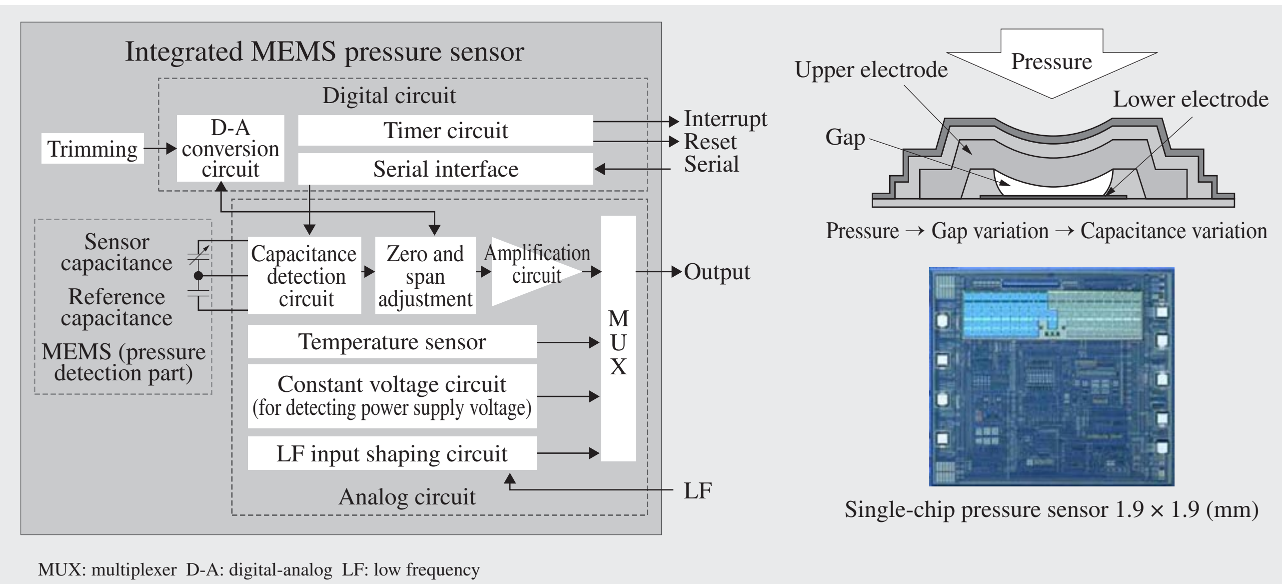

Fig. 5—MEMS Pressure Sensor Principle, Chip Configuration, and Appearance.
The MEMS element and circuit are integrated into a single chip.

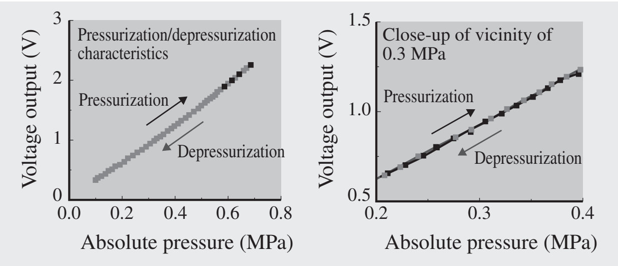

Fig. 6—MEMS Pressure Sensor Characteristics.
Measurements without hysteresis are realized within a range of 0.1 to 1 MPa.

The configuration of the developed pressure sensor and the appearance of the chip are shown in Fig. 5. Electrostatic capacity is used as the pressure detection method in a structure whereby the sensor is built in to the LSI wiring layer. Semiconductor technology is used to form a diaphragm with a narrow gap (0.3 μm). When the external pressure changes, this also changes the diaphragm's gap, which is measured as variation in the capacitance.

Since the LSI and MEMS are directly linked, it is possible to measure minute amounts of capacitance, and extremely high sensitivity is provided.[3] Output characteristics are shown in Fig. 6. Pressurization/depressurization characteristics are achieved without hysteresis.

The standardization of LSI is also progressing, and by modifying the diameter of the diaphragm, it is possible to select a measurement range between 0.1 and 1 MPa. In the future, mounting technology will be developed and reliability will be evaluated as applications are considered.

COMBINED SENSORS FOR VEHICLE CONTROL

Combined sensor for vehicle control are currently being developed for the vehicle stability control system. The vehicle electrical stability control system uses steering angle, automobile angular rate (rotation), acceleration, and other information, which it compares in order to determine the vehicle's skidding. The system then takes the result of this determination and mainly uses it to control the braking force separately for each of the four wheels in order to maintain the right driving state for the vehicle. The combined sensor integrates sensors to measure angular rate and sensors to measure acceleration in two axes (forward and backward as well as side to side), measurements that are necessary for this control.

The National Highway Traffic Safety Administration (NHTSA) in the USA will make the installation of a vehicle stability control system mandatory in stages for all vehicles weighing less than 4.5 t by the MY (model year) 2012. Following North America, there is also a movement towards making this mandatory in Europe as well, and it is predicted that this will also become standard in the Asian region. To apply this to all vehicle types, including compact cars, it will be necessary to reduce costs and simplify installation. The need is increasing for the installation of combined sensor that used to be installed in the vehicle interior in the engine compartment's hydraulic control unit instead. In addition, improvements must also be made in performance, including miniaturization, multi-functioning, and environment-resistance.

Hitachi has now developed a combined sensor in a single compact package that can withstand temperatures in the engine compartment environment ranging from -40 to +125 ℃ (see Fig. 7). In order to support this wide range of temperatures, a structure has been adopted that is robust with respect to the deformations caused by temperatures or mounting[4], and MEMS fabrication

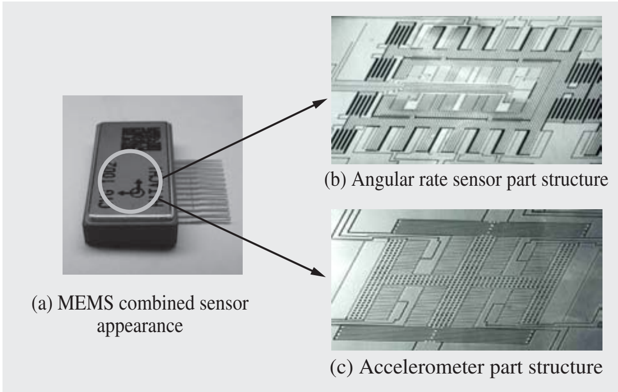

Fig. 7—MEMS Combined Sensor.
The angular rate and acceleration elements are each formed on the silicon substrate and mounted in a single package.

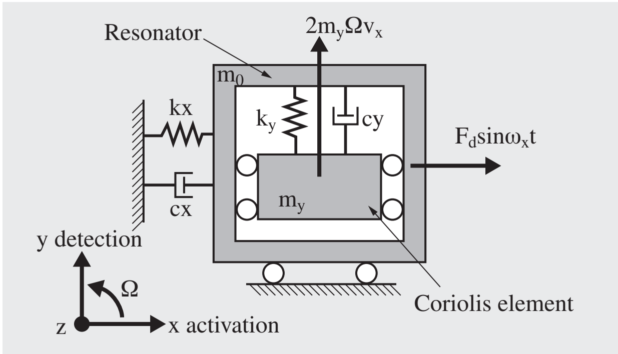

Fig. 8—Angular Rate Sensor Detection Principles.
When the resonator vibrates in the direction of the x axis and an angular rate is applied around the z axis, the Coriolis element is displaced in the direction of the y axis.

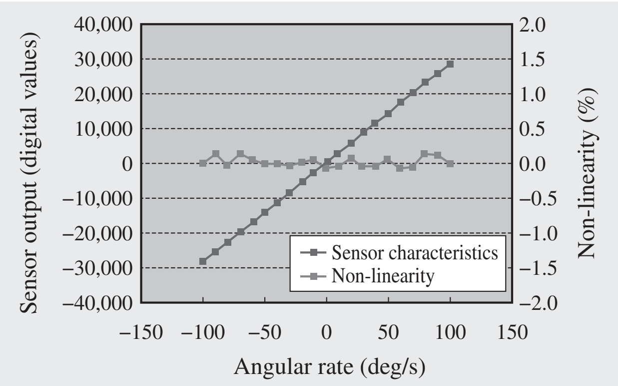

Fig. 9—Angular Rate Sensor Characteristics.
The non-linearity of the angular rate sensor output characteristics is ±0.2% F.S. (full scale) or less.

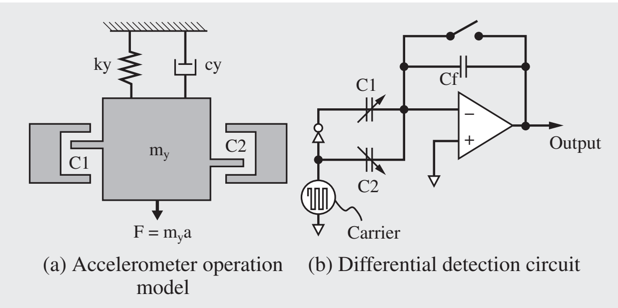

Fig. 10—Accelerometer Detection Principles.
Variation in the two differential capacitors (C1, C2) enables the detection of acceleration (in both x and y axes).

technology is used to form each sensor structure on the SOI (silicon-on-insulator) substrate.

The angular rate sensor's operating principles are shown in Fig. 8. The driving force F_d generated by the electrostatic attractive force causes the resonator to vibrate in the driving direction (x direction). When this happens, the Coriolis element suspended to the resonator with a spring will also vibrate along with the motion of the resonator. When an angular rate is applied around the z axis in this state, Coriolis forces are generated along the detection direction (y axis) perpendicular to both the driving direction (x axis) and the axis around which the angular rate was applied (z axis) in the vibrating resonator and Coriolis element. This causes the Coriolis element to be displaced along the detection direction (y axis) proportionately with the applied angular rate. This displacement is detected as a variation in capacitance, and is output in order to enable the detection of the applied angular rate.

The results of an evaluation of the angular rate sensor's characteristics are shown in Fig. 9. These results show that excellent performance is achieved in a non-linearity of within ±0.2% F.S. (full scale) with respect to the input angular rate.

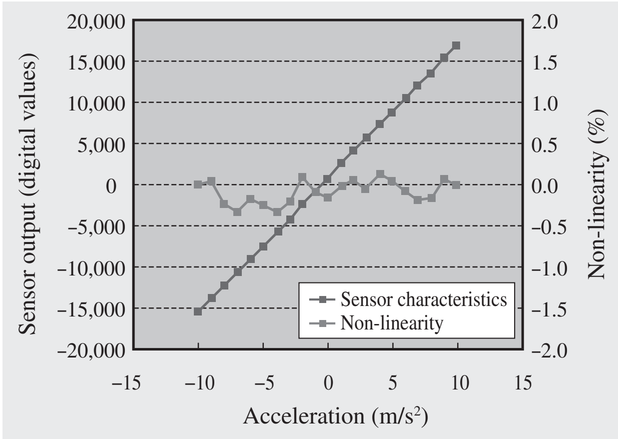

Fig. 11—Accelerometer Characteristics.
The non-linearity of the accelerometer output characteristics is ±0.4% F.S. or less.

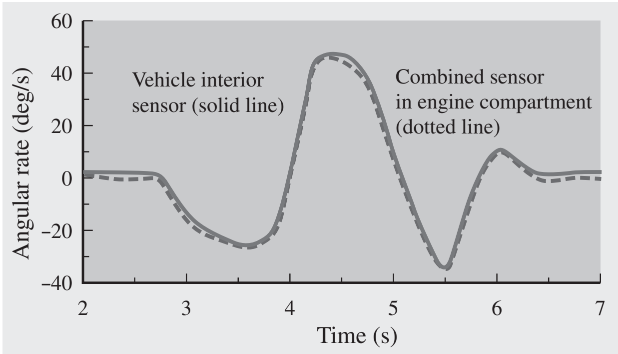

Fig. 12—Combined Sensor Cold Region Testing with Actual Vehicles.
The angular rates from the vehicle interior sensor and the combined sensor are synchronized, making it possible to accurately measure vehicle behavior.

The detection principles of the two-axis accelerometer, which is a combined sensor also incorporating an angular rate sensor, are shown in Fig. 10. The movable part m_y is displaced as acceleration is applied, and variations in the capacitance of the two differential capacitance detection electrodes C1 and C2 located in the direction of detection make it possible to output acceleration as an electric signal.

As shown in the characteristic evaluation results in Fig. 11, non-linearity is held to within ±0.4% F.S. for the accelerometer as well.

The results of combined sensor cold region testing with actual vehicles performed by Hitachi Automotive Systems, Ltd. at test courses in Tokachi, Hokkaido in February 2009 are shown in Fig. 12.

This testing verified that the behavior of combined sensor installed in the engine compartment matches the behavior of traditional sensors installed in the vehicle interior, and that the vehicle's behavior can be suitably detected.

Mass production is now being planned with an eye towards the commercialization of these combined sensor.

CONCLUSIONS

This article discussed development trends in Hitachi's MEMS sensors for automobiles, including MEMS airflow sensors for measuring airflow, single-chip pressure sensors integrating both MEMS and signal processing circuits, and combined sensor for vehicle stability control that enable the measurement of both two-axis acceleration and one-axis angular rate.

The application of MEMS technology has made it possible to miniaturize, integrate, and combine automobile sensors while contributing to the computerization of automobiles, reductions in gas emissions, and improvements in safety. Hitachi plans to continue expanding the range of products applying MEMS while contributing further to the environmental-friendliness and safety of automobiles.

Finally, please note that part of this development was made possible with aid from the "Highly Integrated, Combined MEMS Production Technology Development Project," which is a national project of the New Energy and Industrial Technology Development Organization (NEDO).

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