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A Particulate Matter Sensor with Groove Electrode for Real-Time Diesel Engine On-Board Diagnostics

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Abstract

A particulate matter sensor fabricated by MEMS process is proposed. It is developed to accommodate Euro6 on-board diagnostics regulation for diesel automobile. In the regulation, emission of diesel particulate matter is restricted to 9 mg/km. Particulate matter sensor is designed to use induced charges by charged particulate matter. To increase sensitivity of the sensor, groove is formed on sensor surface because wider surface area generates more induced charges. Sensitivity of the sensor is measured 10.6 mV/(mg/km) and the sensor shows good linearity up to 15.7 mg/km. Also its minimum detectable range is about 0.25 mg/km. It is suitable to detect failure of a diesel particulate filter which should filter particulate matter more than 9 mg/km. For removing accumulated particulate matter on the sensor which can disturb normal operation, platinum heater is designed on the backside of the sensor. The developed sensor can sense very low amount of particulate matter from exhaust gas in real-time with good linearity.

Keywords : Sensor, Particulate matter, Diesel engine, Automobile

1. INTRODUCTION

In the automotive, lots of fatal pollutants are produced such as sulfur oxides and NOx gas. Particulate matter is one of the harmful components discharged from the vehicle. Particulate matter refers to microscopic particles that consist of elemental carbon and combustion by-product. Since the size of each fine particle is smaller than 1um, it may adversely affect to penetrate deeply into alveoli of human [1, 2].

Diesel particulate filter (DPF) is installed downstream of the engine in order to reduce the amount of PM emitted from the diesel vehicles [2]. Most particulate matter is filtered by normal DPF installation. But if it breaks down due to causes such as aging, particulate matter will not be filtered. So, on-board diagnostics regulation is made to detect whether the normal operation of the exhaust emission control system. In Europe, Euro6 regulations, it must be able to measure 9-12 mg/km particulate matter for diesel vehicles which will be sold after 2014. Conventionally, it has been determined whether the failure of the DPF from the pressure difference information obtained by mounting the pressure sensor on the DPF front and rear ends. But, in this method, it is impossible to measure the amount of particulate matter of lower than 13-22 mg/km. Therefore, a new PM sensor can diagnose whether failure of the DPF to accommodate Euro6 OBD regulation is necessary.

Various methods are proposed a method for measuring suspended particulate matter in the air. One of the method to measure the microscopic particles in air uses its optical properties When the light passes the exhaust gas, the optical absorption phenomenon depending on the amount of particulate matter included, such as scattering occurs and the intensity of light changes. Optical method is mostly used to measure the particulate matter, but it°Øs not suitable to attach to the vehicle [3].

Differential mobility analyzer (DMA) is another way to measure the amount of particulate matter. After charging particulate matter by corona discharge, electric field is applied to it. Moving distance of particulate matter by the

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field is changed depending on the weight. This method has an advantage of being able to know with the mass and the number of particulate matter, while it requires very high voltage [4].

B. Park developed a method of using paddle-type piezoelectric resonator which detects the weight of the particles. Because resonator frequency characteristics is determined by the spring constant and the mass, precipitated particles on resonator mass changes the resonating frequency. It is possible to measure the weight of the particles directly, it is characterized with high sensitivity. This method requires means of particulate matter removal and the structural stability in the exhaust gas flow [5].

Bosch company developed a particulate matter sensor of electrical resistivity method. If particulate matter is accumulated between two electrodes, it is detected by measuring their resistance. This method is simple and inexpensive, easy to install, but it can be affected by temperature and humidity [6].

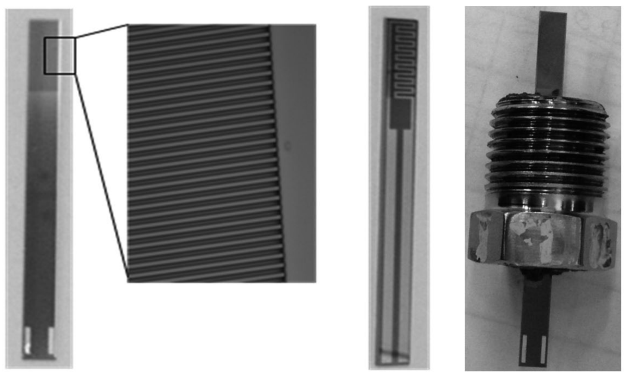
Honeywell developed particulate matter sensor of charge induction method with Minnesota University. This method measurs the amount of charge induced in the sensor electrode by charged particulate matter which moves through the peripheral of the sensor. To install each particulate matter sensor in the front and rear ends of DPF, it is determined whether the damage of the DPF from the difference of the signals of the both sensors. While it has an advantage of real-time measurement, two same sensors are required [7]

We developed a silicon particulate matter sensor using the MEMS process. In order to detect the particulate matter, charge induction method is used. To increase sensitivity of the sensor, sensor surface is increased by formation of groove. Then, to prepare a heater on the backside in order to remove the particulate matter accumulated on the sensor surface. In this paper, we describe fabrication process and the property proposed particulate matter sensor.

2. DESIGN AND FABRICATION

2.1 Sensor

The principle of the sensor that was proposed in this paper is the charge induction by charged particles. When the charged particles pass through the sensor surface, the amount of charge induced in the electrode with grooves are more than planar electrode. Increase induced charge increases sensitivity of the sensor. To increase sensitivity we formed groove pattern with width 10 um and depth 40 um by deep reactive ion etching process. Silicon oxide 100 nm is deposited to prevent the particulate matter from impinging directly on the electrode and additional silicon nitride 100 nm to prevent oxidation caused by high-temperature exhaust gas. On the back side of silicon wafer, platinum heater is patterned to remove the particulate matter accumulated on the surface of the sensor. Fig. 1 is a photograph of the rear and front of the sensor element and packaged sensor with a bolt and ceramic past. In order to measure the particulate matter sensor, it is necessary to fix the sensor element to the pipe.



(a) (b) (c)

Fig. 1. Photograph of (a) front, (b) backside of sensor element, and (c) packaged sensor.

2.2 Heater

Particulate matter is accumulated on the surface of the sensor which is exposed to exhaust gas for a long time. Since particulate matter is a fine particle of which diameter is smaller than 1㎛, it can fill the groove of the silicon. So, accumulated particulate matter should be removed periodically. Main component of the particulate matter is elemental carbon which can be oxidized at high temperature of 650°C. By using heater for raising the temperature locally in the sensor unit, accumulated particulate matter is removed. We placed the platinum heater in the form of a zig-zag on the backside of the sensor unit. Fig. 2. shows simulation (COMSOL) of the temperature distribution when 20 W power is applied to platinum heater. We confirmed the sensory temperature of the surface beyond 650°C by the heat generated from the back of the sensor unit.

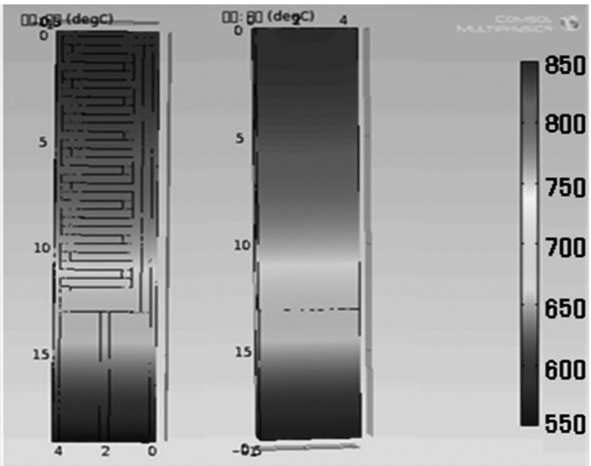


Fig. 2. Simulation result of temperature distribution platinum heater with 20 W applied power.

3. RESULTS AND DISCUSSIONS

3.1 Experiment setup

Experiments were performed using a test single-cylinder diesel engine in order to understand the characteristics of the sensor and the measurement of particulate matter generated in the engine operating condition. Single-cylinder diesel engine used in the experiment has engine cylinder and head made in D2.0 Euro4 specification. Fig. 3 is a photograph of a single-cylinder diesel engine used in the experiment. It is operated at 1500 rpm and the emission of particulate matter is controlled by fuel injection pressure.

Fig. 4 is a schematic of experimental setup for measuring the fabricated particulate matter sensor. After connecting the bypass pipe to the exhaust pipe, sensor is installed to be exposed to sampled exhaust gas. To control exhaust gas flow, valve is connected to the bypass pipe. Additionally electric heater covers the pipe to remove condensate water which generates from sudden temperature decrease. To measure the amount of particulate matter emitted from the single-cylinder diesel engine AVL smoke meter was connected to the exhaust pipe. This is an apparatus for measuring the mass of PM per unit volume of the exhaust gas.

Particulate matter sensor unit is connected to charge amplifier which converts the amount of charge induced in the sensor to voltage. Conversion ratio of the charge amplifier is 2×10^{12} V/C. Charge amplifier output is connected to the DAQ board and output voltage signal is read at the sampling rate 5000 Hz. Circuit and sensor, DAQ board is shielded to prevent the induction of charge by external electric field. After 60 Hz noise filtering is followed to the output signal, root mean square value of signal is calculated.

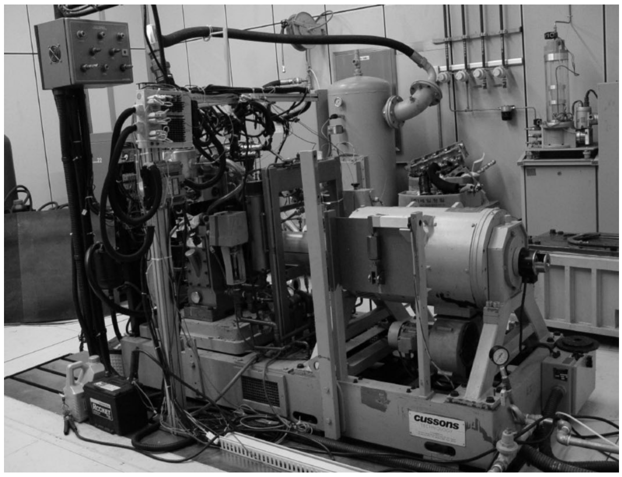


Fig. 3. Photograph of a single-cylinder diesel engine used in sensor measurement.

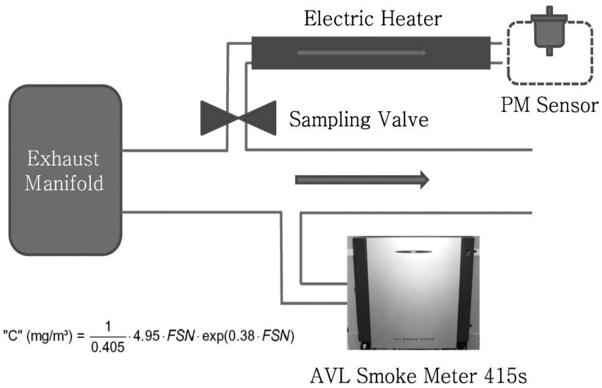
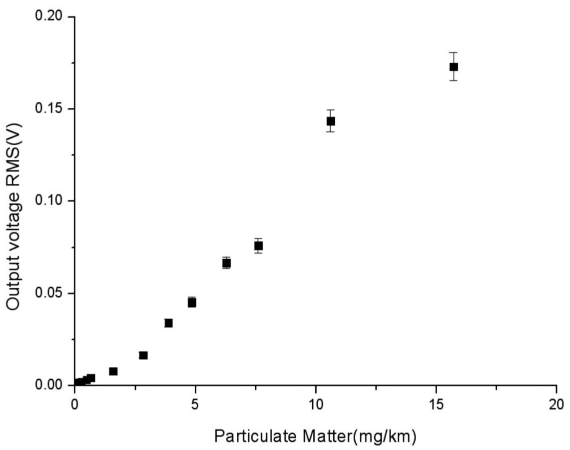


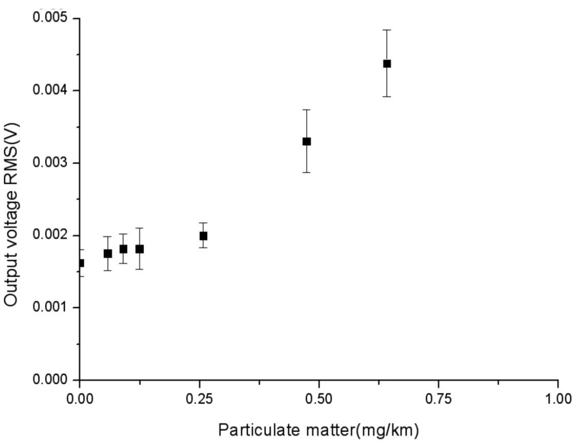
Fig. 4. Schematic of experimental setup for measuring the fabricated particulate matter sensor.

3.2 PM sensor measurement result

Fig. 5 is a sensor output voltage RMS graph of 0-15.7 mg/km particulate matter emissions. Fig. 6 is a sensor output RMS graphs in a narrow range of 0-0.651 mg/km. RMS value can be sure that it increase linearly particulate matter emissions. Sensitivity of the sensor was measured at 10.6 mV/(mg/km). If the particulate matter emissions are lower than 0.25 mg/km output voltage is not linearly decreased any more. It is due to sensor signal is lower than noise. So the proposed sensor can be used to measure the amount of particulate matter more than 0.25 mg/km. In motoring state which emits only gas without particulate matter, the output signal is measured in 1.62 mV. It is not signal by particulate matter.



(a)



(b)

Fig. 5. Sensor output voltage RMS graph for each particulate matter emissions ; (a) 0-15.7 mg/km particulate matter emissions and (b) 0-0.641 mg/km particulate matter emissions.

Fig. 6 is a FFT graph of sensor output signal in a state where 15.7 mg/km particulate matter emission. In the single-cylinder diesel engine emits exhaust gas once per two cycles Therefore, exhaust gas has a pulsation frequency of 12.5 Hz when operation at 1500 rpm. Because particulate matter is emitted with gas together, the same frequency characteristics appear in the output signal of the sensor. Frequency component of the multiple of 12.5 Hz is the harmonic component. Due to 60 Hz noise filtering widely, there is no peak of the 62.5 Hz.

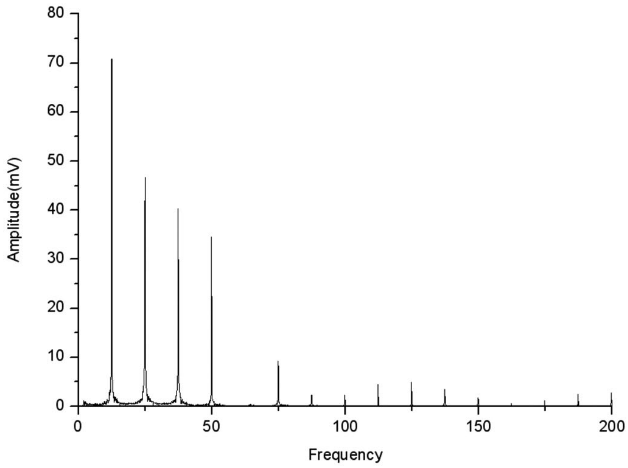


Fig. 6. FFT graph of sensor output signal for particulate matter emission 15.7 mg/km.

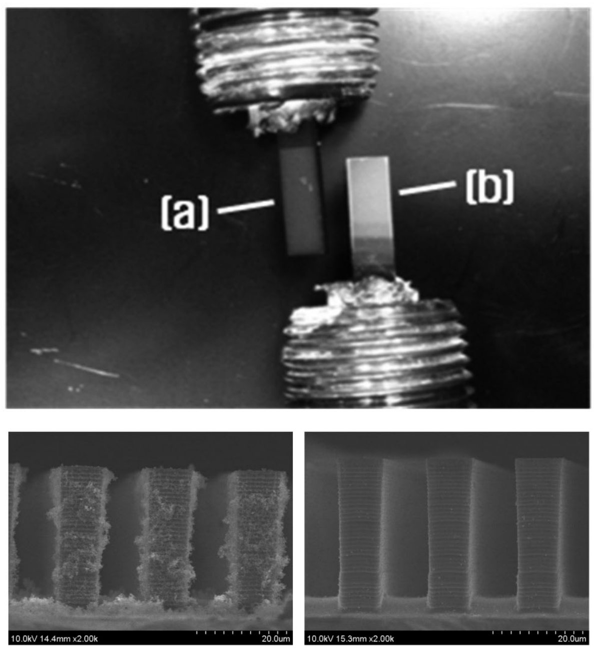
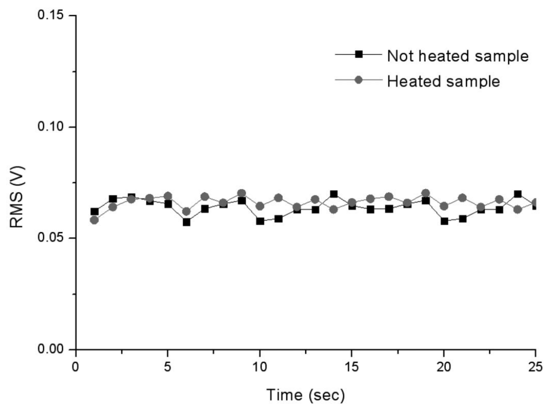


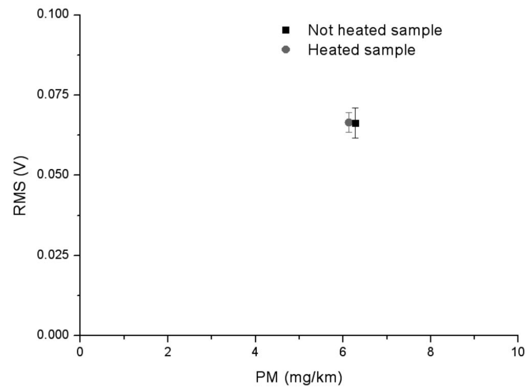
Fig. 7. Photograph of sensor surface with accumulated particulate matter ; (a) before heating and (b) after heating.

3.3 Heater result

If the sensor is exposed to exhaust gas for a long time, fine particles are attached to the surface and change it blackly. Fig. 7(a) is a photograph of the sensor that is exposed about 40 minutes to particulate matter. When viewed in the SEM pictures, a number of particles can be seen inside the groove. While Fig. 7(a) is not heated, Fig. 7(b) is heated for 10 seconds which 20 W power is applied to the heater in order to remove the accumulated particulate matter. From SEM photograph, tiny particle is removed clearly by heat.



(a)



(b)

Fig. 8. Graph of output voltage RMS for not heated sample and heated sample ; (a) Sensor output voltage variation in time and (b) Sensor output voltage RMS versus the amount of particulate matter emission.

To compare the output signal between new sample and heated sample, each sensor is exposed to similar amounts of particulate matter. Fig. 8(a) is a graph of each sensor output signal voltage RMS for each second and Fig. 8(b) is a graph of each sensor output voltage RMS versus the amount of particulate matter emission. When the not heated sample is exposed to particulate matter 6.28 mg/km, the average of sensor output voltage RMS is 66.3 mV and its standard deviation is 4.73 mV. When the heated sample is exposed to particulate matter 6.13 mg/km, the average of the sensor output voltage RMS is 66.5 mV and its standard deviation is 3.09 mV. Difference of the average output voltage is only 0.2 mV which is lower than standard deviation.

4. CONCLUSIONS

Particulate matter sensor with heater for Euro6 regulation is proposed. It is fabricated by MEMS process. To increase the sensitivity of the sensor groove pattern is formed by deep reactive ion etching process. Proposed sensor has sensitivity of 10.6 mV(mg/km) and more than 0.25 mg/km particulate matter can be measured. When 20W power is applied to the embedded heater for 10 seconds, it is confirmed that accumulated particulate matter on sensor part is completely removed. And sensor performance has repeatability after the heating process.

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