

Using Thin Film Sensors to Measure Dynamic Forces Transmitted at Bolted Joints of Vehicles

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ABSTRACT

High sensitivity and capacity thin film pressure sensors using the piezoresistive effect of ytterbium (Yb) thin films have been developed on metal plates using semiconductor manufacturing technology. The pressure sensors can effectively operate in the temperature range of -30 °C to 120 °C due to the thermally stable polycrystalline phase of ytterbium thin films. The sensors clamped at bolted joints on body mounts show excellent dynamic response comparable to that of a load cell.

INTRODUCTION

Dynamic forces transmitted at bolted joints of vehicles have become a crucial factor for designing parts and analyzing physical phenomena of vehicles. In the automotive industry, strain gauge-based load cells have been commonly used for this purpose. However, the load cells have a number of beams and structural members that deform when forces are applied to them and are found to have the following negative effects in vehicle tests:

1. Changes in vehicle geometry due to load cell thickness
2. Reduced joint stiffness due to beam deformation
3. Changes in vibration phenomena due to load cell weight and beam deformation

To overcome these effects, thin film pressure sensors that can directly detect contact forces appear promising. Well-known sensing materials include copper-manganese-nickel alloy (e.g., manganin) [1-3],

amorphous carbon [4] and ytterbium [5]. In particular, manganin thin film sensors have been widely studied by other researchers. These piezoresistive materials change their electrical resistance due to applied mechanical stress such as pressure, as shown in Fig. 1. However, the pressure sensitivity of manganin is $2.4 \times 10^{-5} \text{ [MPa]}^{-1}$, which is not enough to detect fine forces in analyzing the dynamic behavior of vehicles.

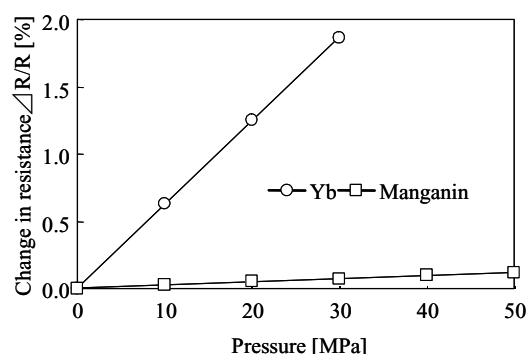


Fig. 1 Pressure Sensitivity of Ytterbium and Manganin Thin Film Sensors

In contrast to the piezoresistive effect, the piezoelectric effect produces electric potential and has very high sensitivity. However, thin film sensors using the piezoelectric effect of aluminum nitride (AlN) and lead zirconium titanate (PZT) can not measure dynamic forces at frequencies less than 0.1 Hz [6], while ytterbium thin film sensors can be applied to the measurement of both static and dynamic forces. Therefore, we have focused on ytterbium with its high sensitivity of $6.0 \times 10^{-4} \text{ [MPa]}^{-1}$.

The purpose of our work is to develop ytterbium thin film pressure sensors that can measure dynamic forces transmitted at bolted joints of vehicles. We have used semiconductor manufacturing technology to develop pressure sensors with thicknesses of about 13 μm on metal plates. This paper reports characteristics of the sensors under different experimental conditions and demonstrates their application potentiality.

MEASUREMENT PRINCIPLE

Crystal lattice strain of compressively-stressed ytterbium films induces changes in carrier density and mobility, which are measured as changes in electrical resistance.

Figure 2 illustrates the structural image of a multilayered thin film pressure sensor. The sensor is fixed between SUS304 plates with a through-hole in the center for application to a bolted joint. It includes a temperature-measuring element made of copper-nickel (Cu-Ni) alloy as well as a pressure-measuring element to prevent it from being highly sensitive to temperature changes. The temperature-measuring element's linear response to temperature is used to compensate for temperature drift of the pressure-measuring element.

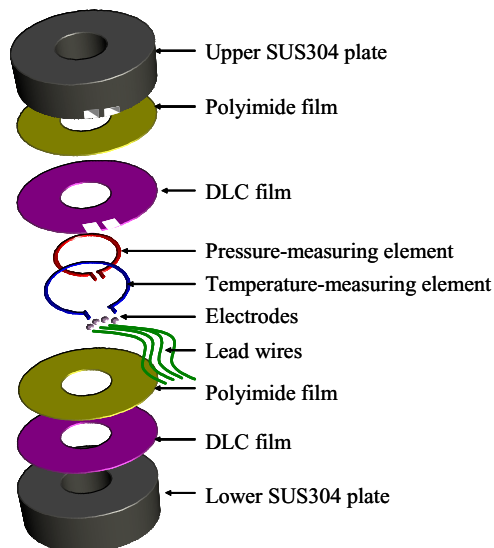


Fig. 2 Structure Image of Thin Film Pressure Sensor

A change in pressure ΔP is calculated using the following equation:

$$\Delta P = \alpha (\Delta R - \beta \Delta r)$$

where ΔR is the change in resistance of the pressure-measuring element, Δr is that of the temperature-measuring element, α is pressure sensitivity, and β is the ratio of the temperature sensitivity of the temperature-measuring element to that of the pressure-measuring element. The sensor's temperature

compensation performance is especially good under an experimental environment in which the ambient temperature changes rapidly, or one in which the temperature of the sensors is not equivalent to the ambient temperature. This is because these two types of elements fabricated closely on the same substrate can respond simultaneously to changes in temperature due to their negligibly small heat capacitances.

SENSOR FABRICATION

Two problems we needed to address in developing thin film pressure sensors were their poor durability and low yield. We were able to address them by improving the sensors' insulator and passivation films. Specifically, we used the plasma chemical vapor deposition (PCVD) method to develop a highly wear-resistant and insulating diamond-like carbon (DLC) film. The properties of the DLC films depend on the hydrogen content added to them. The films we developed, having hardness of 1000 Hv and electric resistance of about $10^9 \Omega \text{ cm}$, were deposited at a low temperature of less than 120 $^{\circ}\text{C}$ so that they would not negatively affect the ytterbium thin film properties. This is an important point because ytterbium films are more easily oxidizable and have poorer adhesion than other electronic materials.

We describe below the manufacturing process of the thin film pressure sensors. First, the DLC films are deposited as insulator films on mirror-polished lower SUS304 plates. Next, the spin-coating method is used to coat polyimide films on the DLC films to improve adhesion between the DLC films and the metal films that are deposited later. Then, terminals formed from titanium (Ti) thin films are patterned in order to electrically connect the pressure- and temperature-measuring elements to the lead wires. After that, temperature-measuring elements are formed from Cu-Ni alloy thin films. Pressure-measuring elements made of ytterbium thin films are then patterned and SiO_2 thin films are deposited in-situ to prevent oxidation of the ytterbium thin films. As shown in Fig. 3, the pressure-measuring element's pattern is designed so as to be effectively subject to mechanical pressure.



Fig. 3 Photograph of Pressure- and Temperature-Measuring Elements

All of these terminals and elements are deposited using the physical vapor deposition (PVD) method and the patterning is performed using metal masks. Next, DLC

passivation films are deposited to mechanically and chemically protect the sensor surfaces from foreign material-induced damage. Polyimide films are then spin-coated as buffer layers on the upper SUS304 plates to ensure that uniform pressure is applied to the pressure-measuring elements. Finally, the upper and lower plates are applied and tightened down with screws. The thickness of the sensors is about 13 μm , not counting the lower and upper plates. Both the Yb/Ti and Cu-Ni alloy/Ti contacts were found to exhibit low resistance and good thermal stability.

CRYSTAL STRUCTURE ANALYSES OF YTTERBIUM THIN FILMS

After assembling, we analyzed crystal structures of the ytterbium thin films. Figure 4 shows bright and dark field images of the films obtained with a cross-sectional transmission electron microscope (TEM). We found that the films consist of fine crystal grains with mean size of 50–80 nm and often contain columnar grains, as well as large grains typically about 300 nm in size. Figure 5 shows a TEM bright field image of the fine crystal grains and the corresponding electron beam diffraction (EBD) pattern. The results obtained indicate that the fine crystal grains are in polycrystalline phase.

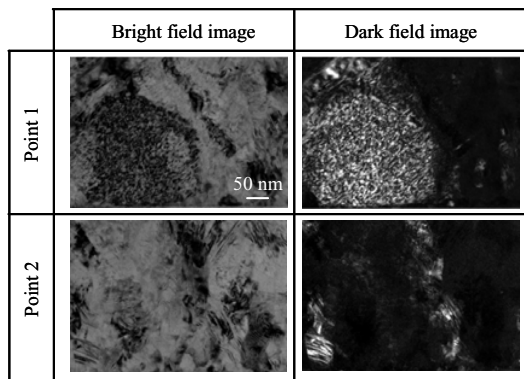


Fig. 4 TEM Bright and Dark Field Images of Ytterbium Film

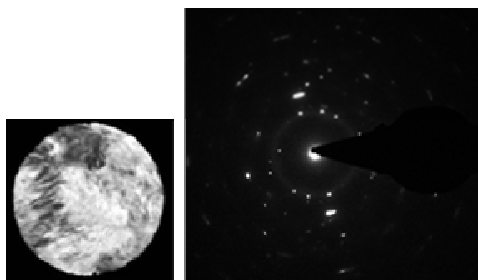


Fig. 5 TEM Bright Field Image of Ytterbium Film (Left) and Corresponding EBD Pattern (Right)

We also used X-ray diffraction (XRD) analysis to investigate the effects of post-heat treatment on the films' crystal structures. Figure 6 shows XRD results of

ytterbium thin films before and after post-heat treatment and intensity ratios of a standard XRD pattern of ytterbium with a face-centered cubic (FCC) structure. As a result of peak profile analysis, some diffractions of ytterbium and SUS304 were detected from each sample, and down-slope profiles of the DLC films were observed around $2\theta=20^\circ$. We found that the films have dominant Yb (111) and Yb (200) orientations [7]. However, some unidentified XRD peaks were present. Table 1 summarizes peak positions (2θ), lattice constants (d), and integral width (β) of the Yb (111) and Yb (222) diffractions. As shown in Table 2, lattice distortions (η) in the films are obtained from gradients of the straight lines of Williamson-Hall plots.

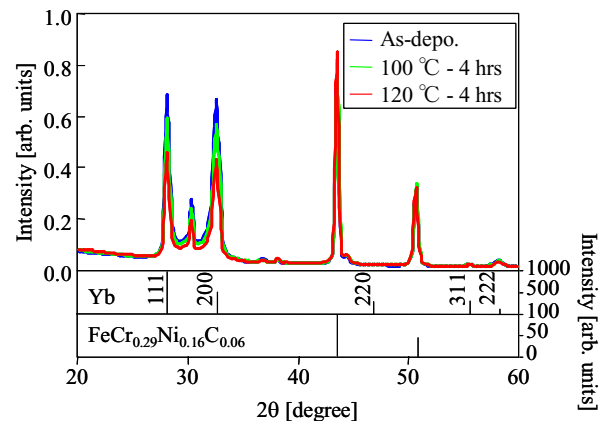


Fig. 6 XRD Patterns of Ytterbium Films

Table 1 Diffraction Peak Data of Ytterbium Films

Sample	h	k	l	$2\theta(\text{degree})$	$d(\text{nm})$	β
As-depo.	1	1	1	28.12	0.3171	0.39
	2	2	2	58.17	0.1585	0.68
Post heat 100 °C-4 hrs	1	1	1	28.12	0.3171	0.39
	2	2	2	58.17	0.1585	0.67
Post heat 120 °C-4 hrs	1	1	1	28.09	0.3174	0.38
	2	2	2	58.16	0.1585	0.56

Table 2 Results of Williamson-Hall Analysis

Sample	Gradient	η
As-depo.	0.0193	0.97
Post-heat 100°C-4 hrs	0.0184	0.92
Post-heat 120°C-4 hrs	0.0102	0.51

Consequently, we were able to determine the following:

1. The ytterbium thin films have polycrystalline pseudo-FCC structures with large lattice distortions and are dominantly oriented in the (111) and (200) directions.