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A Study on the Fabrication of an RTD (Resistance Temperature Detector) by Using Pt Thin Film

Jikwang Kim, Jongsung Kim†, Younghwa Shin* and Youngsoo Yoon**

Department of Chemical Engineering *Department of Electrical and Electronic Engineering,
Kyungwon University, San 65, Bokjeong-Dong, Sujeong-Ku, Sungnam 461-701, Korea
**Thin Film Technology Research Center, Korea Institute of Science and Technology,
P.O. Box 131 Cheongrang, Seoul 130-650, Korea
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Abstract−Pt thin film was deposited on alumina substrate by using DC sputter and the serpentine pattern was formed by photolithography to fabricate the resistance temperature detector (RTD). The Pt film was thermally treated and the surface structure of the film and its effect on the electrical resistance were studied. The sheet resistance of the film depends on the thickness and thermal treatment. The developing and etching conditions for serpentine patterning of the film were investigated and various RTD samples were prepared. All of the fabricated RTD's show a good linear variation of resistance with the temperature. The temperature coefficient of resistance (TCR) values of RTD's increased with decreasing film thickness, narrowing pattern line width, and increasing annealing temperature. The highest TCR value was obtained from RTD with 1 mm line width thermally treated at 700 °C and was 3.53×10^3 ppm/°C.

Key words: Resistance Temperature Detector, Photolithography, Sputtering, Sensor

INTRODUCTION

Recently various types of sensors have been developed and used in many electronic parts and devices [Choi et al., 1997; Jung et al., 1998], and the sensor markets in industrialized countries have been growing at an average rate of 10% [Okamura, 1997]. There have been numerous efforts and investments in sensor research and development. In fact, temperature sensors cover more than 39% of the total number of worldwide produced sensors, especially for industrial use. Temperature sensors are widely used in many home appliances, automotive, laboratory and industrial instruments [Dauphinee, 1982]. They can be categorized into contact and non-contact types by temperature measuring method [Whang, 1994]. The non-contact type sensors, which are based on thermal emission of electromagnetic radiation, are used mainly in research and development fields. The contact type sensor includes thermocouples, thermistors, and resistance temperature detectors (RTD) which are based on the Seebek effect, temperature sensitive electrical resistance, and positive temperature coefficient of electrical resistance, respectively [McGee, 1988]. At present, thermocouples and thermistors are most widely used in industry. A thermistor has high sensitivity, fast time response and low price, but it suffers from limited operating temperature range and nonlinear resistance versus temperature response.

Thin film sensors have received great interest because of their lower consumption of precious materials and high productivity owing to the existing high technology used in the semiconductor industry [Sachse, 1975]. Though their market share at present is not high compared with that of the existing bulky and thick film sensors, they are expected to be used more in the near future with the development of microelectronics. RTD is a thermoresistor whose electrical resistance varies linearly with temperature [Baxter and Freud, 1983]. The sensor has high linearity, stability, and wide operating temperature range, but has a high price and slow response time. In the past most RTD's were wire type, which used thin platinum wire encased in insulated tube as the sensing element, but thin film types of RTD's are now replacing the wire type because of their small dimensions and short response time. In this study we used thin film platinum as the sensing material for RTD's. The film was deposited by DC sputter [Jeon et al., 1999] and annealed at various temperatures. The surface structure and sheet resistance of the film were investigated by XRD, SEM, AFM, and 4-point probe. The dependence of electric resistance of the film on the heat treatment and film structure was studied. The process variables for photolithography of Pt film were optimized to fabricate RTD's with serpentine pattern. The electrical resistance of the RTD's was measured with the ambient temperature varied to investigate the dependence of TCR values on the film thickness and thermal history of RTD's.

EXPERIMENTAL

1. Thin Film Deposition and Characterization

The thin film Pt was deposited by using DC sputter. As the substrate, 99.6% alumina with one side polished ($10\times15\times1$ mm^3) was used. The substrate was cleaned by tetrachloroethylene, acetone, methanol, ethanol, and deionized (DI) water, and dried at 90 °C for 30 min in a drying oven. A 99.999% Pt target with 4 inch diameter was used for the deposition. The working pressure was 5×10^{-3} torr with DC power of 420 V×0.24 A, and the chamber was purged by Ar for 30 min before sputtering. The thickness of the film was controlled by the deposition time. The film was thermally treated in a tubular furnace at various temperatures. Several measurements and tests were performed on the Pt film before and after thermal treat-

†To whom correspondence should be addressed.
E-mail: jskim@mail.kyungwon.ac.kr

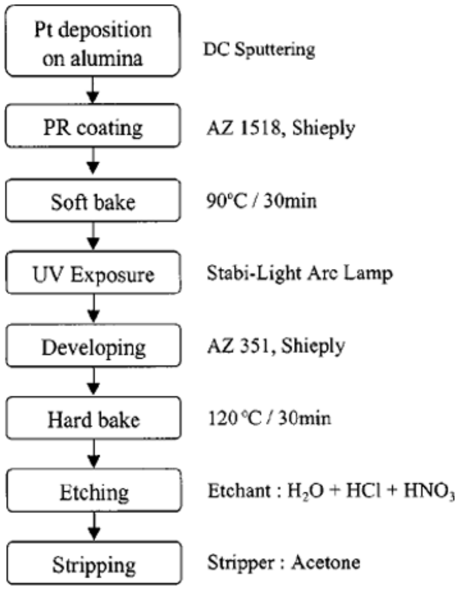


Fig. 1. Flow chart of photolithography process for RTD fabrication.

ment. The thickness of the film was determined by using a surface profilometer (α-step, Tencor). The sheet resistance was measured by 4-point probe (Changmin Tech.). For structural and morphological characterization, XRD (X-ray diffraction, Phillips), SEM (Scanning Electron Microscopy, Akashi Co.), and AFM (Atomic Forces Microscopy, PSI) were used.

2. RTD Fabrication and Resistance Measurements

The serpentine pattern of Pt film was obtained by photolithography [Elliot, 1982]. Positive photoresist (AZ1518) and developer (AZ351) purchased from Shieply were used for the patterning of Pt film. Fig. 1 shows the photolithography process. The photoresist was coated on the Pt film with a manual spinner (Able). The coated photoresist was soft baked at 90 °C for 30 min. The UV light exposure was done by using the Stabi-Light Arc Lamp System (Altech). The UV light exposure time and the developer concentration were adjusted to get the proper serpentine pattern. The detailed process conditions will be discussed in the next section. The etching solution was prepared by mixing HCl and HNO_3. After developing and hard baking, the unprotected Pt film was chemically etched. By stripping the remaining photoresist in acetone, the serpentine pattern of Pt was obtained. Several RTD samples were prepared by changing the line width of the pattern and process conditions.

Fig. 2 shows the fabricated RTD's with various serpentine pattern line widths. The two ends of the pattern are bonded to bigger Pt pads by Al wire (99.95%, EMS). The electrical resistance of the RTD's with various temperatures was measured in a temperature controllable chamber. The TCR value was calculated from the resistance at 0 and 100 °C.

RESULTS AND DISCUSSION

Fig. 3 shows the sheet resistance and resistivity variation of Pt film with annealing temperature for thickness of 105 and 206 nm. The samples were thermally treated at various temperatures in N_2 for 1 hr. After thermal treatment the samples were cooled to room

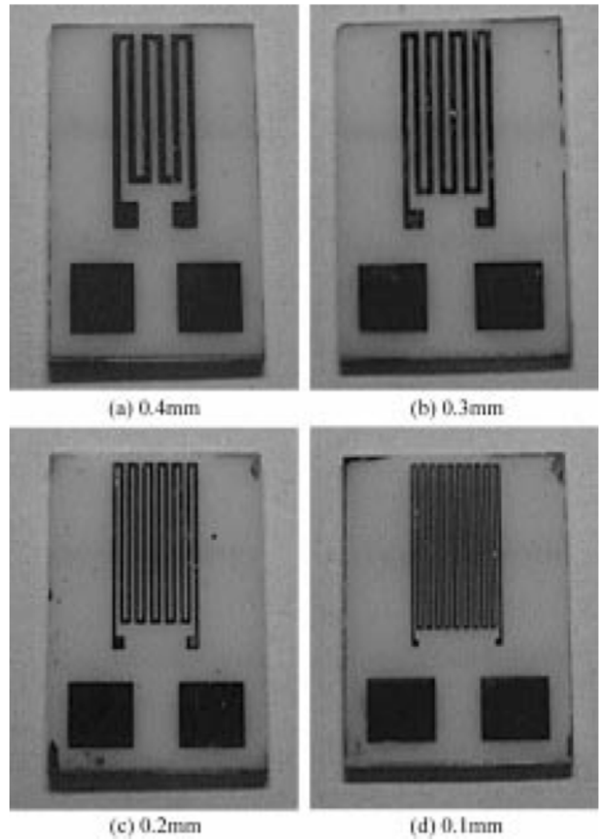


Fig. 2. RTD sensors fabricated via photolithography with various line widths.

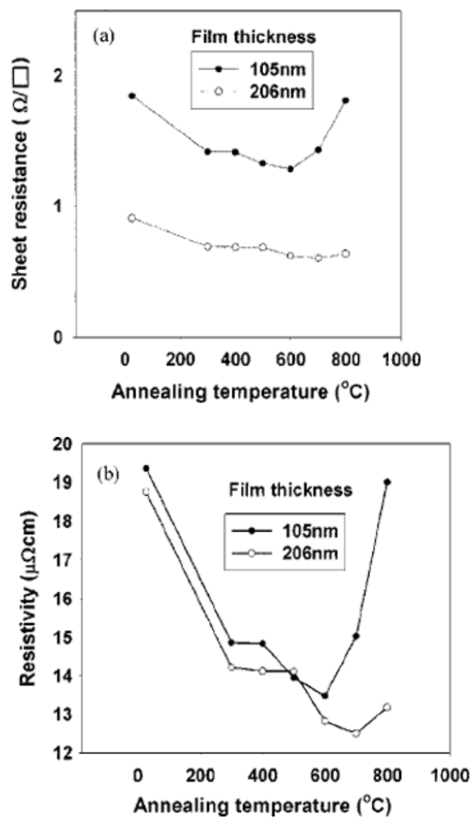


Fig. 3. Effect of annealing temperature of Pt film on the (a) sheet resistance and (b) resistivity.

temperature and their sheet resistance was measured; the resistivity was calculated from sheet resistance and film thickness. The sheet resistance and resistivity start to decrease as the annealing temperature increases, reaching a minimum around 600-700 °C. It is speculated that the sheet resistance decrease is due to the vacancy coalescence by the grain growth and the increase is due to the island formation and dislocation propagation [Lourenco et al., 1998]. The lowest resistivity of the film with a thickness of 206 nm was 12.7 μΩcm, which is close to the value of bulk platinum, 10.5 μΩcm [Kennedy, 1983].

Fig. 4 shows X-ray diffraction (XRD) patterns of the Pt thin film annealed at various temperatures for 1 hr in N_2. The film with a thickness of 206 nm was used for XRD, SEM, and AFM study. The XRD pattern of the film was obtained by using a CuK_α line (λ= 1.542 Å) and Ni filter. The figure shows only Pt (111) reflection at 2θ=39.7° which can be found in an FCC Pt crystal, and the peak intensity increases with the annealing temperature. This shows that the film grows preferentially in (111) plane with a similar structure to an FCC Pt crystal, and higher annealing temperature enhances the crystal growth.

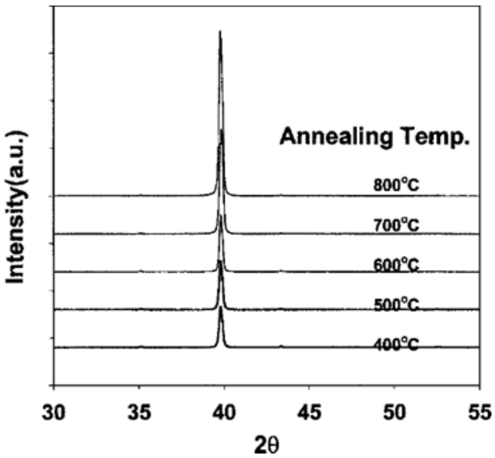
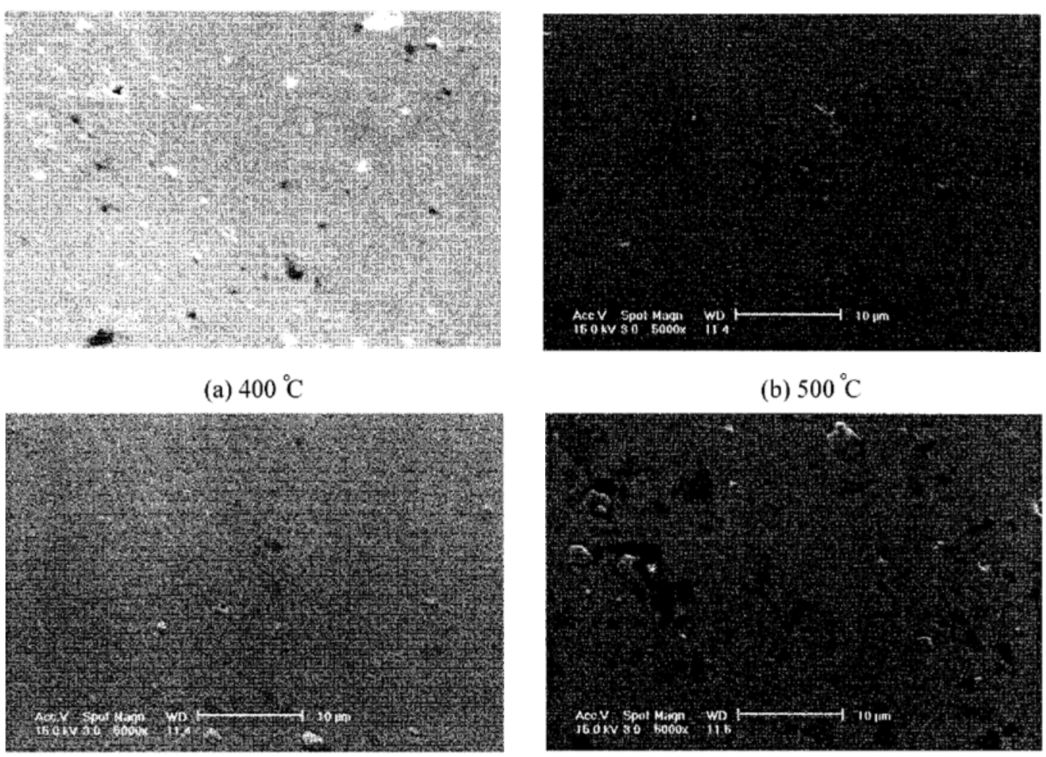


Fig. 4. X-ray diffraction pattern of Pt film with various annealing temperatures.

Fig. 5 shows SEM photographs of Pt film annealed at various temperatures for 2 hrs in N_2. As the annealing temperature increases, Pt crystal grains grow and the surface becomes more dense and smooth, but after 700 °C, the grains agglomerate to form clusters. The clusters induce pore formation and make film surface rougher. This tells why the resistivity and sheet resistance of the film reach minimum at about 700 °C.

The surface roughness of the film with various annealing temperatures was measured by AFM. The peak to valley height (R_{p-v}), root mean squared (RMS) roughness, and average roughness are listed in Table 1. Twenty areas of the sample surface were scanned. The surface roughness decreased with the annealing temperature and reached a minimum at 700 °C. From the experiments of sheet resistance, SEM, and AFM, the annealing temperature of Pt film for RTD fabrication was fixed to 700 °C.

Fig. 6 shows a photograph of the photoresist profile after developing and a cross-sectional SEM picture of Pt film after stripping. The photoresist used in this experiment is composed of Novolak resin and photoactive compound such as DNQ [Campbell, 1996]. To get a proper photoresist pattern, the soft baking and developing conditions should be carefully optimized. If the baking time is not enough, the residual solvent hinders photochemical reaction and



(a) 400 °C (b) 500 °C

(c) 700 °C (d) 800 °C

Fig. 5. SEM photographs of Pt film annealed at various temperatures.

Table 1. Surface roughness of Pt film annealed at various temperatures

Annealing temperature (°C)	R_{p-v} (Å)	Rms roughness (Å)	Average roughness (Å)
400	253	19.3	14.7
500	224	18.6	13.6
600	245	17.0	12.0
700	201	16.2	10.5
800	295	20.4	18.5

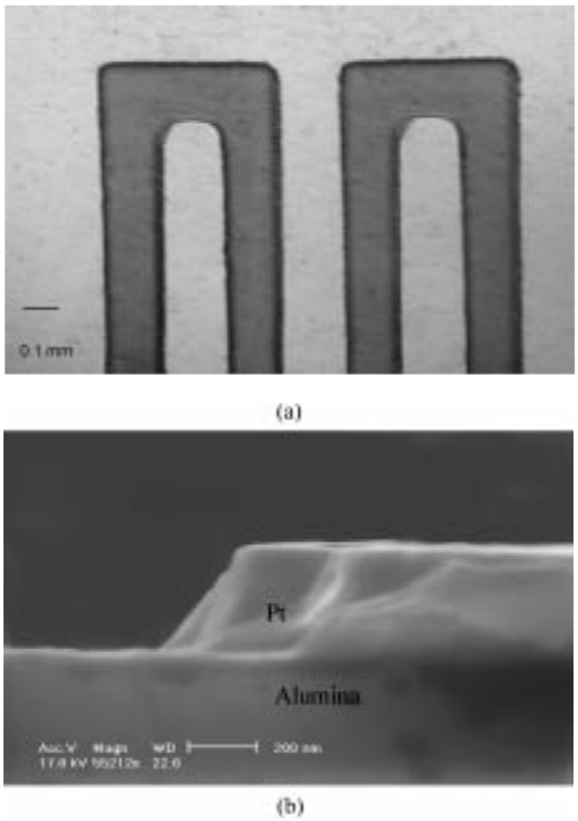


Fig. 6. (a) Photograph of photoresist profile after developing. (b) Cross-sectional SEM picture of Pt film after stripping.

the developing rate is decreased, while overbaking degrades the photosensitivity of the photoresist and this results in a poor image replication.

The UV exposure power and time were set to 500 W and 20s. The developer was diluted with DI water. Under various conditions the photoresist was developed, and the image pattern was examined by optical microscope to optimize the process conditions. Right after the developing, the film was hard baked at 120 °C for 30 min. The chemical etchant for Pt film was prepared by mixing HCl and HNO_3 solution in DI water [Lee, 1991]. The composition and temperature were varied to get optimum etching condition. The serpentine patterning was completed by the immersion of etched Pt film in acetone. The remaining photoresist on the Pt film was easily stripped. Table 2 shows the optimal photolithography process conditions for the serpentine patterning obtained from the above experiments.

Table 2. Process conditions for serpentine patterning of Pt film

Process	Condition
Soft bake	90 °C, 30 min
UV exposure	500 W, 20 s
Developer	Developer : DI water=1 :5 (vol), 50 °C
Hard bake	120 °C, 30 min
Etchant	HNO_3 : HCl : H_2O=1 : 7 : 3 (vol), 90 °C
Stripper	Acetone

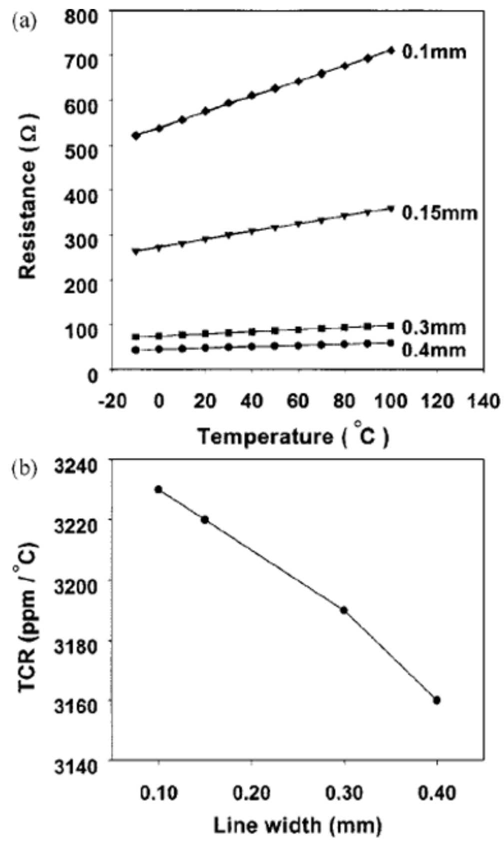


Fig. 7. Effect of pattern line width of RTD on the (a) resistance variation with temperature and (b) TCR value.

Fig. 7 shows the effect of pattern line width of RTD on the resistance variation with temperature and TCR value. The Pt film was annealed at 600 °C for 1 hr, and the thickness was 206 nm. The temperature coefficient of resistance (TCR) is defined as the relative resistance change per degree measured over the interval 0 and 100 [Dziedzic et al., 1997]. The figure shows that the resistance of the samples varies linearly with temperature, and as the line width of the Pt RTD increases, the resistance and TCR value decrease. As the line width increases, the cross-sectional area of the metal increases, and this results in decrease of resistance. As the slope of resistance decreases with line width, the TCR value also decreases. This shows that to increase TCR value, the pattern line width should be decreased and higher resolution patterning is necessary.

Fig. 8 shows the effect of annealing temperature of Pt film on the resistance variation of RTD with temperature and TCR value. The RTD samples annealed at 600-700 °C show lower resistance than that annealed at 500 °C. It seems that the Pt crystals do not grow

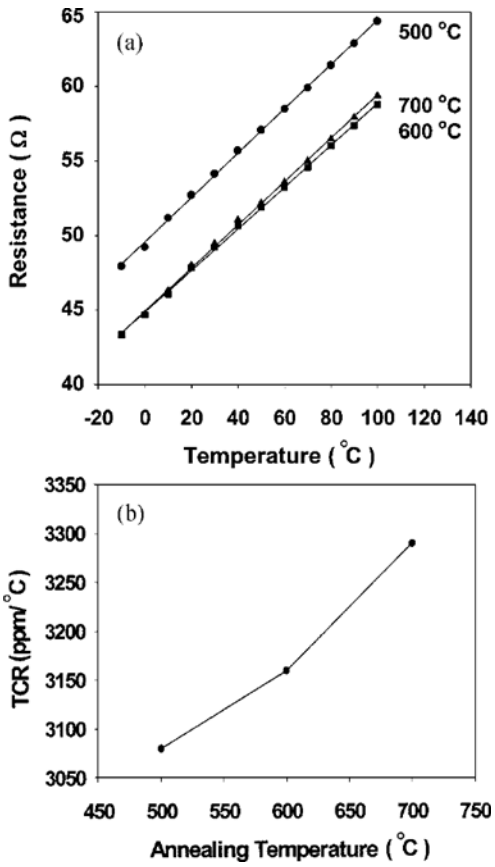


Fig. 8. Effect of annealing temperature of Pt film on the (a) resistance variation with temperature and (b) TCR value.

well at 500 °C, and this results in high resistance. The figure also shows that the TCR value increases with the annealing temperature. This suggests that the annealing temperature of the film affects the crystal growth, hence the electrical resistance and TCR value.

Fig. 9 shows the resistance variation of RTD with temperature change for different thickness. The thicker one shows lower resistance and its TCR value is 3.16×10^3 ppm/°C and the TCR value of

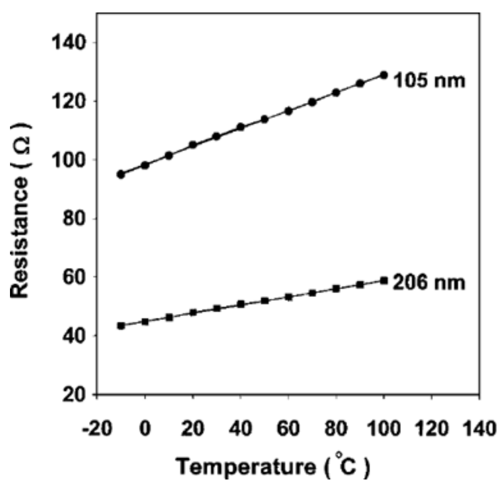


Fig. 9. The resistance variation of RTD with temperature change for different thickness.

the thinner one is 3.14×10^3 ppm/°C. Although all RTD samples prepared showed good linear resistance variations with temperature change, their resistance and TCR value were very dependent on various process parameters. The sputtering conditions for film deposition and other process conditions including pattern design, photolithography, and heat treatment should be optimized to fabricate RTD's with proper resistance ranges and TCR values. The highest TCR value obtained from the RTD samples was 3.29×10^3 ppm/°C. This was not close to the industrial standard value, 3.85×10^3 ppm/°C [Diehl and Koehler, 1998], so the control of resistance and TCR together with sensor device fabrication will be the subject of future work.

CONCLUSIONS

Resistance temperature detector was fabricated by using Pt thin film through DC sputtering and photolithography process. The sheet resistance and resistivity of Pt film strongly depend on the thickness and surface structure. The XRD experiment shows that the film grows preferentially in the (111) plane with a similar structure to an FCC Pt crystal, and higher annealing temperature enhances the crystal growth. The sheet resistance and resistivity of the film were changed due to the crystal growth and cluster formation, and showed the lowest value when annealed at about 700 °C. The optimal process conditions for serpentine patterning of Pt film by photolithography were investigated, and various RTD samples were prepared. The resistance of the fabricated RTD shows a good linear variation with the temperature change. The resistance and TCR value of the RTD samples were dependent on various parameters such as the film thickness, serpentine pattern line width, and annealing temperature. The highest TCR value was obtained from RTD with 1 mm line width thermally treated at 700 °C and was 3.53×10^3 ppm/°C.

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