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TEMPERATURE MEASUREMENTS WITH MICRO-TFTCS

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We fabricate metal thin film thermocouples (TFTCs). Au-Pt, Cu-Ni, and W-Ni are deposited on a glass plate using standard thin film processes. The dimension of thermocouple junction is 300μm×300μm. The thermoelectric powers of TFTCs are different from those of bulk because diffusion of electrons is restricted by the very thin film. However TFTCs are still useful for temperature measurements because the thermoelectric voltage is proportional to measured temperature at thermocouple junction. The response time of Au-Pt TFTCs is about 30ns when the surface of the glass is heated by a YAG pulsed laser. The result compares favorably with measurements by a thermoreflectance method. We also describe W-Ni nano-TFTCs with micro-heater fabricated by Focused Ion Beam for the measurement of absolute temperature distribution in 10 micron area. In order to reduce the size of the TFTCs we employ a 3-dimensional structure.

Keywords: *Temperature measurement, MEMS, TFTCs, Focused Ion Beam*

INTRODUCTION

In recent years the micro-fabrication systems have been well developed, and fabricated sub-micron structures have been applied to electric devices, μ-TAS, MEMS and so on [1]. For microelectronics power dissipation and elevated temperature in high density chips has been important issues. It is essential to develop a technique for measurements of temperature in sub-micron area [2,3]. IR micro-scope is popular method, but the spatial resolution is limited by infrared wave length. Scanning thermal microscopy (SThM) is proposed to get temperature distribution image in sub-micron [2-5]. Thermal scanning is achieved by using a very small temperature sensor on the end of a tip of atomic force microscope (AFM). The spatial resolution is about 20nm but the experimental results of SThM tend to decrease further than actual temperature, since a liquid film exists between the tip and the sample surface [3,5]. The liquid film becomes dominant as thermal resistance. The tip-sample heat conduction mechanism is complicated and is not still understood fully. Moreover the time response of SThM is slow, because whole large probe must become a steady state thermally [5]. Meanwhile, thin film thermocouples (TFTCs) have been investigated in recent years [6-10]. Thin films are deposited on a sample directly. Heat conduction problems without liquid film are simple, so experimental results will be converted to actual temperature without any assumptions about thermal issues. Standard micro-fabrication technique was applied to make TFTCs because pure metals (Au-Pt, Cu-Ni, W-Ni) were used to make the sensors. Spatial resolution and time response are improved by making very small TFTCs.

In this paper we fabricated TFTCs in order to measure the actual temperature in sub-micron area, and to measure very fast transient temperature. Metals were deposited

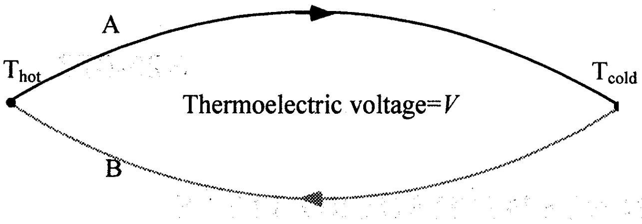
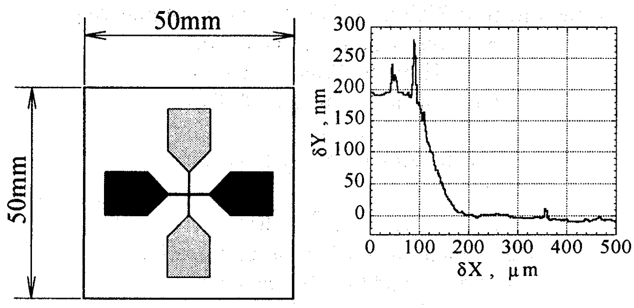


Fig. 1 Thermodynamic circuit for a relative Seebeck coefficient



(a) Top view

(b) Film thinkness(Au) (Au-Pt TFTCs)

Fig. 2 Schematic diagram of thin film thermocouples

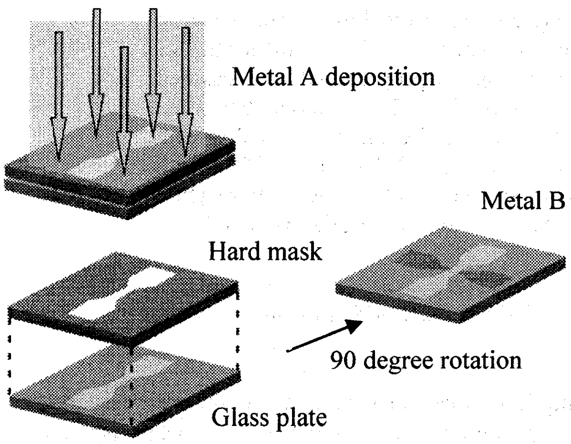


Fig. 3 Thin film thermocouples fabrication

on glass plates and Si wafers. Thermopower of the fabricated TFTCs was calibrated, and then time response of TFTCs was investigated by using a pulsed laser. The temperature distribution measurements were carried out by using mesh type thermocouples. For sub-micron area nano-TFTCs (W-Ni) was made by Focused Ion Beam (FIB). The dimension of thermocouple junctions were about 300nm×300nm.

NOMENCLATURE

a : Thermal diffusivity, m^2/s
E : Energy, J
e : Charge of electron, C

Table 1 Seebeck coefficients of metal (at 300K)

Metal	Seebeck coefficient μV/K
Cu	1.8
Au	1.9
W	11.2
Pt	-3.3
Ni	-14.8

k : Boltzmann's constant, J/K
q : Heat flux, W/m^2
Q : Applied power, W
r : Position, m
S : Seebeck coefficient, V/K
T : Temperature, K
t : Time, s
V : Thermoelectric voltage, V
x : Position , m
δ : Thermal diffusion length, m
λ : Thermal conductivity, W/mK

Subscripts

A : Material A
B : Material B
F : Fermi level
cold : Low temperature
hot : High temperature
0 : Room temperature

FABRICATION OF METAL TFTCS

When two different metals are connected together and the junctions maintained at different temperatures, then a small voltage is generated (Fig. 1). The thermoelectric voltage depends on the difference of temperature between T_{hot} and T_{cold} as follows:

$$V=\int_{Tcold}^{Thot}(S_A - S_B)dT \qquad (1)$$

A large difference of Seebeck coefficients is favorable for temperature measurements. Seebeck coefficients of deposited metals are shown in Table 1 [11]. Au-Pt, Cu-Ni, and W-Ni were chosen as the two elements of the TFTCs to generate large thermoelectric voltage. Seebeck coefficients of semiconductors and alloys are larger than those of metals [11], but we deposited pure metals to make TFTCs for simplicity of fabrication. Metal thin films were fabricated on 2mm-thick glass plates by using a heating technique and sputtering. Fine wires of pure Au(99.99%), Ni(99.99%), and Cu(99.99%) were evaporated by tungsten coils. Metals with high melting point (Pt (99.99%), W (99.99%)) were deposited by sputtering. Glass plate was well cleaned in ultrasonic bath with acetone, methanol, and iso-propanol. Good adhesion between metals and glass plates was obtained even without adhesion layer. Hard masks were used to pattern thin films (Fig. 2). The dimensions of the TFTCs are: cold-hot junction distance longer than 15mm;

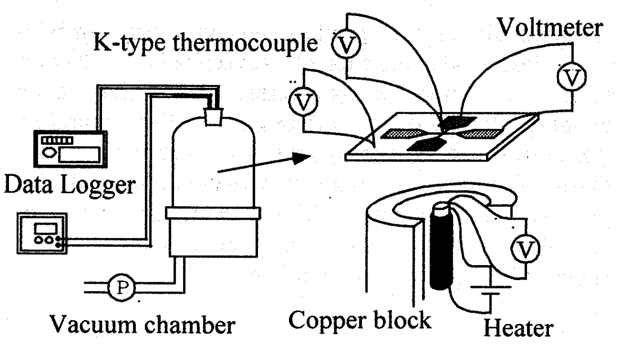


Fig. 4 Experimental setup for thermopower measurements

two metals junction widths equal to 300μm (Fig.3 (a)). Film thickness (Fig.3 (b)) was very thin (50-200nm), and it was comparable to the mean free path of electrons in metals (20-50nm).

THEMOPOWER MEASUREMENT

To measure Seebeck coefficients of metal TFTCs, thermocouple junction was heated by using Nichrome wire and a cold junction was kept at constant temperature by using copper block with cooling water (Fig.4). Calibration was conducted in vacuum chamber to stabilize the thermoelectric voltage. Heat capacity of TFTCs is very small, so measured thermoelectric voltage was fluctuated by even small convection effects in atmosphere. Temperatures at junctions were measured by K-type thermocouples. Thermoelectric voltage was measured by using a high resistance voltmeter (Yokogawa 7555). The calibration results of TFTCs are shown in Fig. 5. Thermoelectric voltage is proportional to the temperature at hot junction. Seebeck coefficient S is expressed as follows [12]:

$$S = -\frac{\pi^2 k^2 T}{3|e|E_F}\left(\frac{3}{2}+m\right) \qquad (2)$$
$$\tau(E) = BE^m$$

Electrons are diffused from a hot junction to a cold junction, then thermoelectric voltage is generated. Parameter m in Eq. (2) includes complicated effects of diffusion of electrons in metals. The difference of Seebeck coefficients among samples is explained by parameter m. According to Eq. (2) Seebeck coefficient is constant under the same averaged temperature $T(=(T_{hot}+T_{cold})/2)$. Thermoelectric voltage is proportional to the temperature difference between hot junction and cold junction, and the difference of temperature is converted into thermal voltage by Seebeck effect. Both experimenta' results and theoretical results suggest that TFTCs is still useful for temperature measurements.

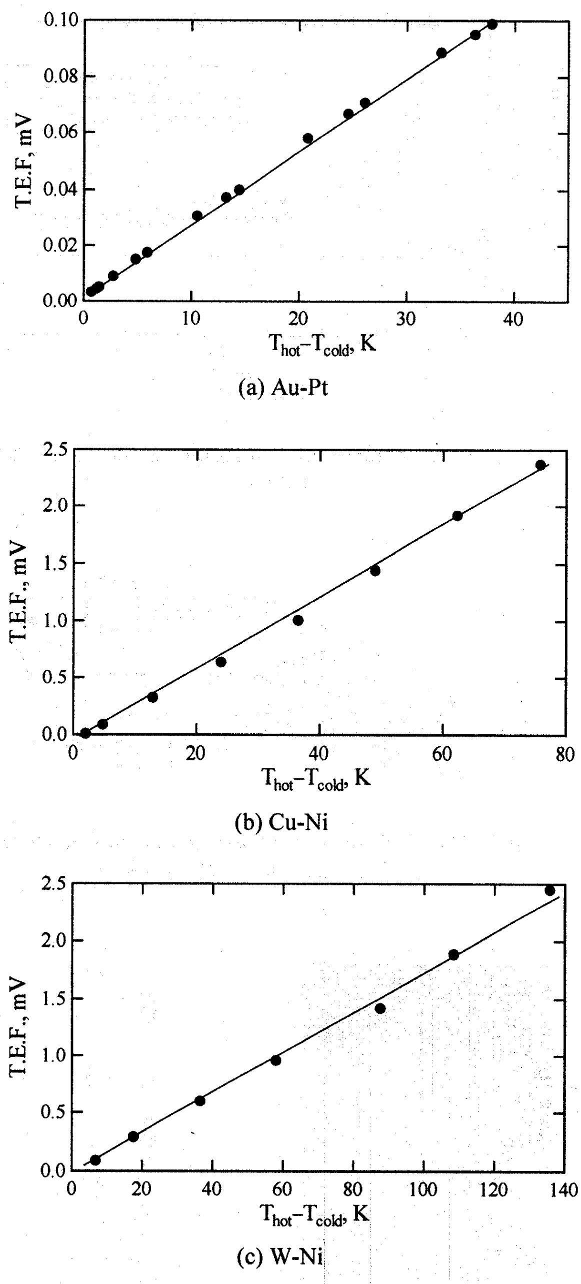


Fig. 5 Thermoelectric voltage vs temperature calibration of TFTCs

TIME RESPONSE OF TFTCS

Transient thermal response of TFTCs (Au-Pt) was measured by using a YAG pulsed laser with a pulse width 9ns as a heat source. The laser beam was focused in a 10mm diameter spot on the TFTC junction. The dimension of TFTC junctions was much smaller than that of a laser spot. Therefore 1-dimensional thermal conduction equation can be applied to predict transient temperature of a sample surface during heating by pulsed laser [13]. Thermal diffusion length δ is given by

$$\delta = \sqrt{4at} \qquad (3)$$

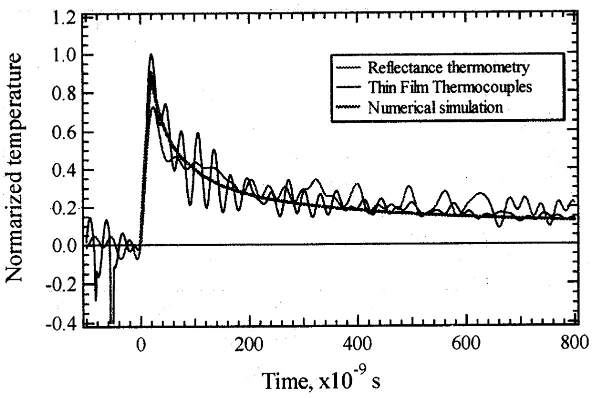


Fig.6 Transient temperature response for Au-Pt TFTCs on a glass plate

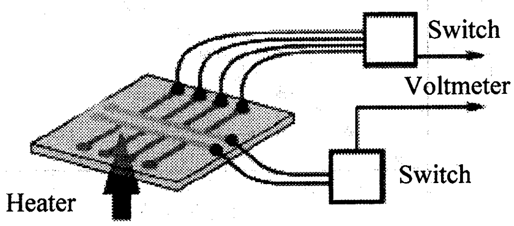


Fig.7 Schematic diagram of temperature measurements by using mesh type TFTCs (Cu-Ni)

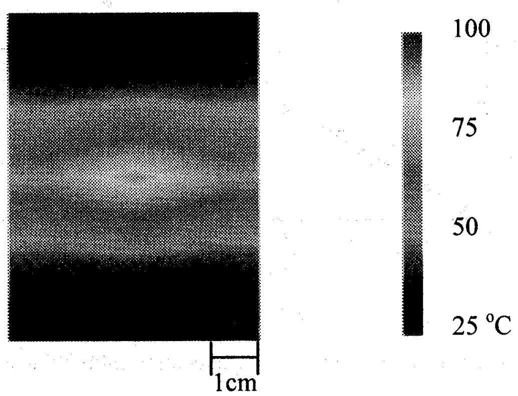


Fig.8 Measured temperature distribution by using mesh type TFTCs (Cu-Ni)

Using the thermal diffusivities of Au(128×10^{-6}m^2/s) and a pulse width 9ns, the depth of heat penetration into the sample during the laser pulse is obtained 2.1μm. Thermal diffusion length of TFTCs with Au surface is over 10 times longer than its own thickness, and metal thermal conductivity is much larger than that of a glass plate. The temperature of TFTCs becomes relatively uniform after heating by a pulsed laser. Measured transient temperature by Au-Pt TFTCs on a glass plate is shown in Fig. 6. Temperature of the sample surface was also measured by thermoreflectance method [14] simultaneously, and temperature at surface exposed by a pulsed laser was calculated numerically. Plotted results were non-dimensionalized by using each maximum temperature difference. Five hundred experimental results were averaged to reduce the noise. Results of both experiments and numerical simulation agree well each other. TFTCs responded transient temperature in 30ns, and the characteristic thermal response of TFTCs was extremely fast.

MEASUREMENT OF TEMPERATURE DISTRIBUTION

To measure temperature distribution on a surface of a glass plate, mesh type TFTCs was deposited as shown in Fig. 7. Cu-Ni was chosen as two component metals for thermocouples. Eight thermocouple junctions were patterned by using a hard mask. A tungsten heater was put under a 2mm thick glass plate. Measured results are shown by a counter plot (Fig. 8). Temperature distribution in 3cm×5cm was obtained at room temperature to 100°C. To improve the spatial resolution of the sensors, nano-TFTCs were fabricated on a Si wafer with micro-heater as shown in Fig. 9 by using Focused Ion Beam (SII JIB2300). A SiO_2 layer as an insulator was thermally grown on Si wafer in a furnace. Ni film was deposited on a SiO_2 surface as the one component of TFTCs. Second SiO_2 insulator was deposited by using a spin coater and baking the sample. To make thermocouple junctions, through holes were opened by using FIB. The opened holes were filled up with W, and W nano-wires were drawn by using FIB. Three thermocouple junctions were fabricated in 10μm area from a heater (Fig. 10). The dimension of thermocouple junctions was 500nm×500nm . The heater was 200nm thick, 2.5μm width, and 30μm long. We measured thermoelectric power of W-Ni TFTCs around the heater applied 25, 30 and 45mW electric power. We estimated the temperature distribution by using Fourier's law (Fig. 11).

$$q=-\lambda\frac{\partial T}{\partial r} \tag{4}$$

For the simplicity we assumed that effects of both thermal radiation and convection were very small, and temperature at $x=\infty$ was room temperature T_0. Applied electric power Q to the micro-heater was controlled, therefore heat flux q at r was calculated by using semi-sphere surface area $2\pi r^2$.

$$\frac{Q}{2\pi r^2}=-\lambda\frac{\partial T}{\partial r} \tag{5}$$

The solution of Eq. (5) was obtained;

$$T = \frac{Q}{2\pi\lambda r} + T_0 \tag{6}$$

We calibrated thermopower of nano-TFTCs by using Eq. (6). Experimental results and estimated temperature distribution were shown in Fig. 12. We fit the experimental results on the estimated temperature distribution by assuming thermopower. The best thermopower for fitting was 21.5μV/K. The thermopower of nano-TFTCs was reasonable value compared with that of large W-Ni TFTCs(17.9μV/K) although the analytical model was very simple. For the precise calibration, a detailed analytical model is necessary. We fabricated three thermocouples in 10 μm for the measurement of absolute temperature. The spatial resolution was much better than that of IR microscope.

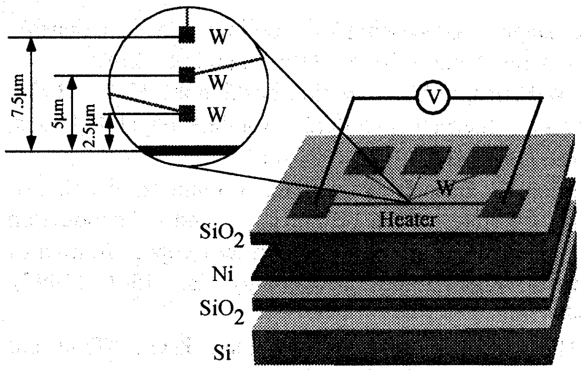


Fig. 9 Schematic diagram of nano-TFTCs (W-Ni)

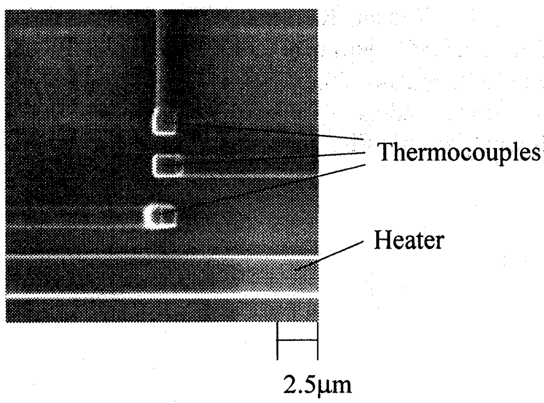


Fig. 10 A SEM image of nano-TFTCs (W-Ni) with micro-heater

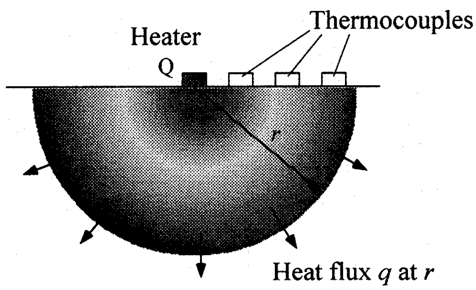


Fig. 11 Schematic of analitical model

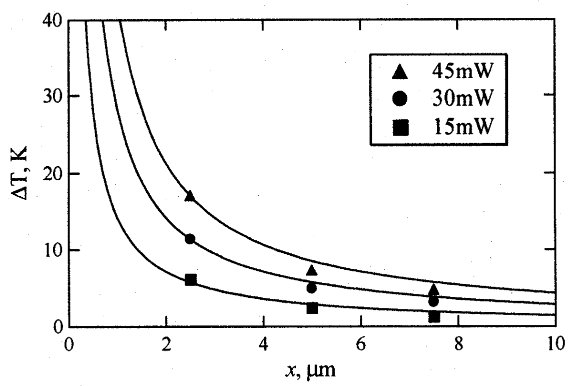


Fig. 12 Temperature distribution measured by using nano-TFTCs

CONCLUSION

Metal thin film thermocouples were made by using standard thin film processes. Seebeck coefficients of TFTCs were smaller than those of bulks, but TFTCs was still useful to measure temperature because thermoelectric voltage was proportional to the temperature difference between hot junction and cold junction. Heat capacity of TFTCs is very small and the thickness of TFTCs is very thin, so transient temperature of a glass plate surface in 30ns was measured well. Temperature distribution in 3cm×5cm of a glass plate surface was also measured by mesh type TFTCs. Experimental results ranged from room temperature to about 100°C. To improve the spatial resolution, nano-TFTCs (W-Ni) was fabricated by using FIB. The dimension of thermocouple junctions was 500nm×500nm. The 20 °C temperature rise was measured in 10μm. The spatial resolution was better than that of an IR microscope.

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