

NOTES

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Silicon resistor to measure temperature during rapid thermal annealing

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A resistor composed of a piece of Si wafer and two thin silver wires attached to it, can reliably sense the temperature during rapid thermal annealing (RTA). As constant electric current passes through the Si piece, the resistivity change of Si with temperature produces a voltage signal that can be readily calibrated and converted to an actual temperature of the samples. An accuracy better than $\pm 10^\circ\text{C}$ is achieved between 300° and 600°C .

In recent years, there have been extensive studies in the application of RTA to silicon device technologies.¹⁻³ The common methods to measure temperature during RTA use either an optical pyrometer or a thermocouple, both of which suffer inherent limitations for the accurate measurement of RTA temperatures.⁴ The application of optical pyrometers in a RTA system can be complicated and is subject to problems if all potential sources of errors are not properly considered, especially at relatively low temperatures. With thermocouples, the temperature measured is that of the thermocouple junction, which is not necessarily that of the sample of interest particularly at very short (10 s) times. To securely bond the thermocouple to every sample being annealed could be laborious.⁵

In this work, we present an alternative method to measure the RTA temperature of small individual Si test samples. This method has been applied successfully in our previous work.⁶ The method is based on the principle of the rapid resistivity change with temperature of Si in its intrinsic regime.⁷ The resistor is composed of a piece of a commercially available *p*-type $\langle 100 \rangle$ Si wafer and two thin Ag wires attached to it. The thin Ag wires minimize heat losses and also provide the needed flexibility to place the Si piece in the RTA unit in exactly the same manner as an actual sample in order to exactly reproduce the thermal environment of actual samples. The Ag wire is attached to each end of the Si piece by alloying it between the large Si piece and another small Si piece placed on top. To ensure good wetting, aluminum foil is folded around the wire. The Si pieces are pressed together while heat is applied by a little torch⁸ with a very fine tip. The completed Si resistor is drawn schematically in Fig. 1 (the Si piece is of $1.5\text{--}2.5\text{-}\Omega\text{ cm}$ resistivity, about 2.5 cm long, 0.5 cm wide, and the diameter of the Ag wires is 0.005 in.). The

resistor was first calibrated in an air furnace by measuring the voltage drop across the resistor as a function of temperature, at steady-state condition for constant electric current. The resistor temperature was measured with a digital thermometer whose thermocouple was clamped to it to minimize temperature differences. The voltage reading was linear with the electric current ($I \leq 20\text{ mA}$). One example of the calibration curve for $I = 10\text{ mA}$ is shown in Fig. 2; the estimated calibration error is well within $\pm 5^\circ\text{C}$. The reproducibility is verified; the same output reading is obtained at a given temperature during the heating up and the cooling down cycle of the furnace. Comparisons with a thermocouple contained in the RTA unit (AG Associates, 410 heat-pulse) have also been performed *in situ* at several temperatures. For long RTA cycles ($> \text{a couple of minutes}$), the two readings always agree within about $10^\circ\text{--}15^\circ\text{C}$. This result also eliminates photogeneration of excess free carriers as the

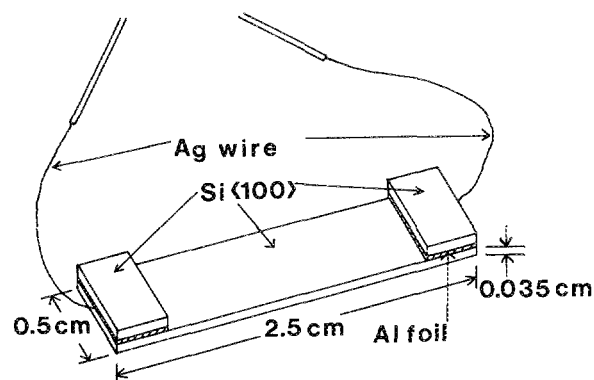


FIG. 1. Schematic drawing of Si resistor.

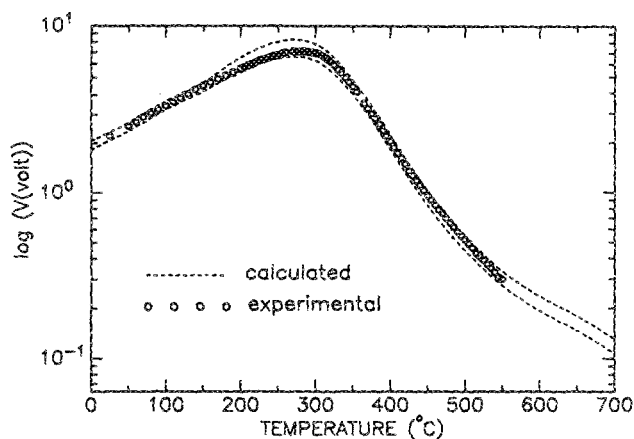


FIG. 2. Plots of voltage change vs temperature with constant current of 10 mA. The dashed lines indicate the range of uncertainty for the theoretically predicted temperature dependence, with the room-temperature point matched to the experimental points indicated by circles.

main process responsible for the conductivity change of the resistor.

Also shown in Fig. 2 are the limits (dashed lines) calculated from the conductivity $\sigma(T) = q[p(T)\mu_p(T) + n(T)\mu_n(T)]$, where q is the electronic charge. The hole and electron concentrations p and n are the equilibrium values at the temperature considered⁷; μ_p and μ_n are the hole and electron mobilities in Si. Their temperature dependence was obtained (or graphically extrapolated) from Figs. 3 and 4 of Ref. 9. In the calculated temperature dependence, the range for the uncertainty that results from the inaccuracy in reading and estimating the numbers from the reference figures is indicated by the two dashed curves. The effective dimension of the resistor for the case of Fig. 2 is taken as 1.5 (cm) \times 0.5 (cm) \times 0.035 (cm) to match the measured and the calculated points at room temperature. The experimental data are in good agreement with the predicted trend. The strong temperature dependence of the resistivity in the temperature range of 300° to 600 °C allows an accurate measurement of the temperature. The resistor is usable above 600 °C, but with decreasing accuracy.

The main advantage of the resistor over a thermocouple is in short time (10 s) measurements. For short RTA runs the resistor temperature is often higher than that of a thermocouple placed in its proximity and touching the substrate (a 4-in. Si wafer) by as much as 50 °C. The resistor reading is more reliable for such short RTAs for at least three reasons: (i) The resistor, being made of Si, couples to the radiation

field of the heat source in the same manner as a Si sample. The temperature actually measured is thus that of an object nearly identical to that of interest. (ii) The resistor has a much faster response than thermocouple. In practice, the reading from the thermocouple approaches that of the resistor for long RTA runs. A pyrometer, which also has a very fast response, responds very similarly at short times to the resistor rather than to the thermocouple. (iii) A pure Al film deposited on an oxidized Si sample exhibits morphological changes (balling up) that indicate the melting of Al when the thermocouple reads about 50 °C less than the melting point of Al. The Si resistor is best suited for the temperature regime 300°–600 °C, which is an important one for many metal-Si reactions. The simplicity, high reliability, and accuracy of this temperature sensor was an essential element in a recent experimental study of the kinetics of silicide formation by RTA.⁶

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⁸Tescom Corporation model 11-1101; tip orifice diam 0.006 in.

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