CYCLIC HEATING OF A FILM ON A SUBSTRATE

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A mathematical model is presented for cyclic heat treatment of a film on a substrate, and heating curves have been constructed for a thin silicon wafer heated by an infrared source and cooled by forced convection.

Heat treatment of films on substrates is important in the production of integrated circuits and semiconductor devices, including drying and polymerization of lacquers, photoresist compounds, firing of current-lead and resistive pastes, forming of metal contact areas, and so on [1]. The films involved in these processes vary in physical composition and in thickness from 0.5 to 50 μm. Strong radiation surces producing a continuous heat supply are used to reduce the heating and drying times [2, 3].

For instance, vigorous heat treatment of a liquid photoresistor layer on a substrate causes the film to heat up much more rapidly than the solvent evaporates by virtue of the small film thickness (0.5-2.0 μm). The rapid temperature rise in the substrate causes a relatively prolonged high-temperature phase in the film, which may adversely affect the physicochemical characteristics. In the case of drying, there is a high temperature gradient from the outside inwards, which retards the motion of solvent and water outwards, which also adversely affects the structural and mechanical properties, and can even give rise to internal stresses tending to break the film if the heat treatment is very vigorous. Consequently, the performance of rapid drying and heating in a film–substrate system is dependent on the detailed organization, which has to provide optimum heating and evaporation rates that are matched to the rates of internal diffusion of water or solvent within the film [3, 4].

Cyclic (oscillating) states are therefore best used in heat treatment of films: alternating heating and cooling at preset intervals. Lykov [5, 6] layed the theoretical basis for such states in drying heat-sensitive materials. Others have also pointed out [7-10] the prospects for using cyclic states in accelerating drying for various materials. Valuable results have been obtained in cyclic drying of heat-sensitive powders [11], for which the Lykov criterion is very small (Lu $\ll$ 1).

However, the technical literature does not deal with the calculation of such cycles on thin plates bearing films. Here we present calculations and kinetic curves for cyclic heating of silicon wafers. A distinctive feature of this mode of treatment is that the temperature of the wafer or film as a function of time takes the form of a curve with a rising oscillation amplitude in the temperature (Fig. 1). The following mathematical model is presented for cyclic heating and cooling to derive the conditions for heating in accordance with the curve of Fig. 1.

During the heating phase, we neglect the radiation back to the source and the heat loss from the surface of the system, since the temperature difference in the thickness (δ = 500 μm) is slight, while for the cooling we assume that the heat transfer from the surface of the film is proportional to the temperature difference ($t_2 - t_c$).

The first cycle is heating of the wafer (heat supplied):

$$cm\frac{dt_1}{d\tau} = q,\ 0 \leqslant \tau \leqslant \tau_1. \tag{1a}$$

The cooling of the wafer (heat loss) gives

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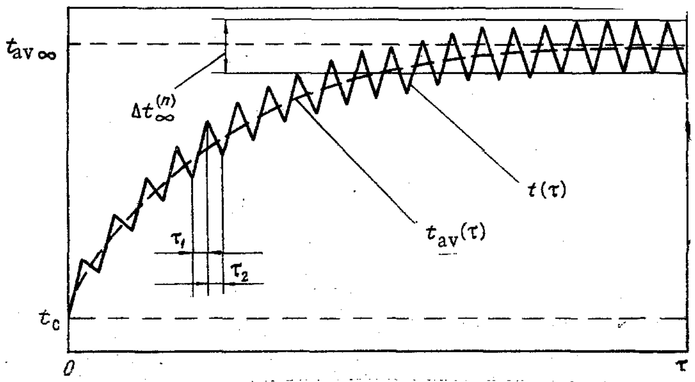

Fig. 1. Response of a thin plate to cyclic heating.

$$cm\frac{dt_2}{d\tau} = -\alpha S(t_2 - t_c),\ 0 \leqslant \tau \leqslant \tau_2. \tag{1b}$$

The mass and thickness (δ = 0.5–2.0 μm) of the film are much less than those of the substrate (δ of 200–500 μm), so m in (1) is the mass of the substrate, and t is the temperature of the film, which is taken as equal to the substrate temperature.

The initial conditions for Eq. (1a) are

$$\tau = 0,\ t_1 = t_0 = t_c. \tag{1c}$$

During heating of the wafer

$$t_1 = t_c + \frac{q}{cm}\tau,\ \ 0 \leqslant \tau \leqslant \tau_1. \tag{1d}$$

The temperature at the end of the first heating cycle is

$$t_1^{(1)} = t_c + \frac{q}{cm}\tau_1. \tag{1e}$$

During cooling, the initial condition for (1b) is

$$\tau = 0,\ t_2 = t_1^{(1)} = t_c + \frac{q}{cm}\tau_1. \tag{1f}$$

Then from (1b) with (1f) we obtain

$$t_2 = t_c + \frac{q}{cm}\tau_1 e^{-\beta\tau},\ \ 0 \leqslant \tau \leqslant \tau_2, \tag{1g}$$

where $\beta = \alpha S/cm$.

The temperature at the end of the first cooling phase is

$$t_2^{(1)} = t_c + \frac{q}{cm}\tau_1 e^{-\beta\tau_2}. \tag{1h}$$

We omit the intermediate steps to obtain for cycle n that

$$t_1^{(n)}(\tau_1) = t_c + \frac{q}{cm}\tau_1(1 + e^{-\beta\tau_2} + e^{-2\beta\tau_2} + \ldots + e^{-(n-1)\beta\tau_2}), \tag{2}$$

$$t_2^{(n)}(\tau_2) = t_c + \frac{q}{cm}\tau_1(1 + e^{-\beta\tau_2} + e^{-2\beta\tau_2} + \ldots + e^{-(n-1)\beta\tau_2})e^{-\beta\tau_2}. \tag{3}$$

If the number of cycles is large,

$$t_1^{(\infty)}(\tau_1) = t_c + \frac{q}{cm}\tau_1\frac{1}{1 - e^{-\beta\tau_2}}; \tag{4}$$

$$t_2^{(\infty)}(\tau_2) = t_c + \frac{q}{cm}\tau_1\frac{e^{-\beta\tau_2}}{1 - e^{-\beta\tau_2}}; \tag{5}$$

$$\Delta t_\infty = t_1^{(\infty)}(\tau_1) - t_2^{(\infty)}(\tau_2) = \frac{q}{cm}\tau_1. \tag{6}$$

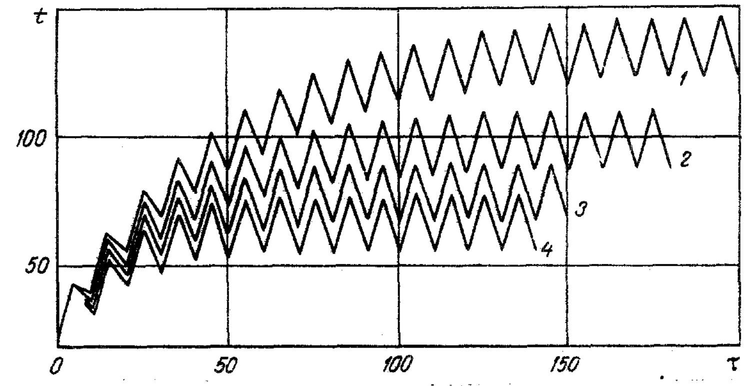

Fig. 2. Temperature of a silicon wafer as a function of time for $\tau_1 = 5$ sec, $\tau_2 = 5$ sec, q = 4.18 W (cooling with forced convective heat transfer): 1) $\beta = 0.04\ \text{sec}^{-1}$, $\alpha S = 3.56 \cdot 10^{-2}$ W/deg; 2) 0.06 and $5.34 \cdot 10^{-2}$; 3) 0.08 and $7.52 \cdot 10^{-2}$; 4) 0.10 and $9.30 \cdot 10^{-2}$.

Consider the ratio of the increments in the temperature oscillation amplitude in the penultimate and last cycles:

$$\frac{\Delta t_1}{\Delta t_2} = \frac{t_1^{(1)}(\tau_1) - t_2^{(1)}(\tau_2)}{t_1^{(2)}(\tau_1) - t_2^{(2)}(\tau_2)} = \frac{1}{1 + e^{-2\beta\tau_2}} < 1. \tag{7}$$

Similarly,

$$\frac{\Delta t_2}{\Delta t_3} = \frac{1 + e^{-\beta\tau_2}}{1 + e^{-\beta\tau_2} + e^{-2\beta\tau_2}} < 1. \tag{8}$$

From (7) and (8) we have

$$\frac{\Delta t_i}{\Delta t_{i+1}} < 1. \tag{9}$$

It follows from (6)-(9) that the heating phases will involve increasing amplitude in the temperature oscillations until the quasistationary state is reached (Fig. 1).

These expressions were used in constructing heating curves for a silicon wafer (D = 40 mm, $\delta = 400$ μm) heated by a quartz tubular radiator [12] and cooled by forced convection.

To reduce the time to reach the quasistationary state, one must increase α in the cooling period, which is attained, for example, in the device by using a gasdynamic support [15], with air streams incident on the plate. Figure 2 shows heating curves for a silicon wafer with forced convective heat transfer. The $t = f(\tau)$ curves have been constructed for q = constant and various α, which were determined by the method of [13, 14]. The curves show that the number of cycles needed to reach the quasistationary state for given q, τ_1, τ_2, and t_c will increase as the heat-transfer coefficient falls, and $t_{av}^{(n)} = 0.5[t_1^{(n)}(\tau_1) + t_2^{(n)}(\tau_2)]$ and $\Delta t^{(n)} = t_1^{(n)}(\tau_1) - t_1^{(n)}(\tau_2)$ increase with the number of cycles n.

In practice, it is often necessary to know the time needed to reach this state, so we derived formulas for the numbers of cycles N and i in which $t_{av}^{(n)}$ and Δt_i, respectively, of the penultimate cycle differ from $t_{av}^{(n+1)}$ and Δt_{i+1} for the last cycle by 5%.

The condition for N is

$$\frac{t_1^{(N)}(\tau_1)}{t_1^{(N+1)}(\tau_1)} \geqslant 0.95; \tag{10}$$

and from (2) we substitute into (10):

$$\frac{\frac{q}{cm}\tau_1 \frac{1 - e^{-\beta\tau_2 N}}{1 - e^{-\beta\tau_2}} + t_c}{\frac{q}{cm}\tau_1 \frac{1 - e^{-\beta\tau_2(N+1)}}{1 - e^{-\beta\tau_2}} + t_c} \geqslant 0.95. \tag{11}$$

Then we have

$$N \geqslant \frac{1}{\beta\tau_2} \ln \frac{(1-0.95e^{-\beta\tau_2})\dfrac{q}{cm}\tau_1}{(1-0.95)\left[\dfrac{q}{cm}\tau_1 + t_c(1-e^{-\beta\tau_2})\right]}. \qquad (12)$$

We substitute (2), (3), (7), and (8) into $\Delta t_i/\Delta t_{i+1} \geq 0.95$ to obtain

$$\frac{1+e^{-\beta\tau_2}+e^{-2\beta\tau_2}+\ldots+e^{-(i-1)\beta\tau_2}}{1+e^{-\beta\tau_2}+e^{-2\beta\tau_2}+\ldots+e^{-i\beta\tau_2}} \geqslant 0.95, \qquad (13)$$

and, finally,

$$i \geqslant \frac{1}{\beta\tau_2} \ln \frac{1-0.95e^{-\beta\tau_2}}{1-0.95}. \qquad (14)$$

From (12) and (14) we readily show that $i > N$, i.e., the quasistationary state for $t_{av}^{(n)}$ is reached earlier than that for $\Delta t^{(n)}$.

These expressions provide heating curves for treatment of thin wafers with known geometrical parameters, specific heat, and mass. During the development of such cyclic processes one has to select the values for q, τ_1, τ_2, α; this model for a flat plate allows one to determine the parameters of the heat treatment from nomograms constructed for particular materials.

NOTATION

τ_1, τ_2	are the cooling and heating time;
c	is the specific heat of substrate;
m	is the mass of substrate with film;
D, δ, S	are the diameter, thickness, and area of plate;
q	is the heat flux absorbed by substrate;
α	is the mean convective heat-transfer coefficient of substrate;
t_0	is the initial temperature of plate;
t_c	is the ambient temperature (air);
$t_1^{(n)}$	is the plate temperature at the end of n-th heating cycle;
$t_2^{(n)}$	is the plate temperature at end of n-th cooling cycle;
Δt_∞	is the constant temperature amplitude after a large number of cycles;
$t_{av\infty}$	is the mean temperature in qusisteady state.

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