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An inverse heat transfer method to provide near-isothermal surface for disc heaters used in microlithography

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Abstract

In microlithography, the fabrication method for semiconductors and MEMS devices, the post-exposure baking process involves the baking (heating) of a 300 mm diameter, ∼1 mm thick silicon wafer substrate with a disc heater to a set point temperature (T_{SET}) triggering the photo-chemical reaction undergone by the photo-resist applied on the wafer. For a known loss occurring due to the convection boundary conditions at the top and side of the disc heater surface, providing a steady state heat power (Q_T, W) as a constant heat flux (q'', W/m^2) over the heater bottom surface (A, m^2) would result in a fixed temperature difference ΔT ($=T_{MAX} - T_{MIN}$) on the heater top surface. Minimizing this heater surface ΔT – an imprint of which is transferred to the heated wafer – is crucial for determining the accuracy of the semiconductor circuit pattern etched on the silicon wafer. To reduce this ΔT further ($\Delta T \to \Delta T_{MIN}$) for identical steady state heat power Q_T, a cost-effective method of two-zone redistribution of the heater bottom surface heat fluxes (two heat fluxes q''_1 and q''_2 given, respectively, to the inner and the outer-zones) is proposed. This inverse heat transfer problem in steady state is verified using numerical methods and scaling analysis from first principles. For given convection heat losses and T_{SET}, the achievable heater surface ΔT_{MIN} decreases as the split radius increases. Also, there exists a critical split radius (r_c) below which no energy need be given to the inner-zone to achieve ΔT_{MIN} (i.e., $q''_1 = 0$). This r_c value is predicted using the theoretical scaling analysis and was found to match excellently with the value obtained from numerical methods. The variations of heater surface ΔT, q''_1/q''_2, and r_c were found to be independent of the T_{SET} and dependent only on the heat losses. Limiting values of achievable heater surface ΔT_{MIN} for various split locations dividing the two-zones of heat flux are also presented.

Keywords: Microlithography; Silicon wafer; Post-exposure bake; Inverse heat transfer; Temperature uniformity; Scale analysis

1. Introduction

Microlithography, a semiconductor manufacturing process, has been used extensively for printing circuit patterns on silicon wafers, semiconductor devices like diodes, transistors, integrated circuits and in the fabrication of MEMS devices used in sensors, actuators and biomedical devices [1–3]. Microlithography involves the deposition, baking and exposure of a photo-resist for building a pattern, and a developing process for washing away the unexposed photo-resist (for positive-imaging resists). A flowchart of the sequential photo-lithography process steps followed almost unaltered in the microlithography industry for the past two decades [1,2] is given in Table 1.

In the present-day industry-standard DUV irradiated, photo-resist lithography process, [4,5], as described in the initial processes of Table 1, the film of polymeric resist is exposed to patterned UV radiation, creating an image of the acid pattern (integrated circuitry) in the film. A subsequent heating step denoted in step 8 of Table 1 as post-exposure bake (PEB) process, alters the solubility of the acidic pattern in the irradiated portions of the film [6]. This allows the desired single layer three-dimensional relief pattern to be retained on the photo-resist film, after subjecting to the develop process in Table 1. The accuracy of circuit patterns generated by the photo-lithography process is assessed using a representative 'critical dimension' (CD)

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Nomenclature

A	surface area (m^2)
CD	critical dimension
DUV	deep ultra-violet
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
MEMS	microelectro-mechanical systems
PEB	post-exposure bake
q''	heat flux (W/m^2)
Q	energy (W)
r	radial co-ordinate, radius (mm)
R	radius of the heater (mm) (=150 mm), Fig. 1
t	thickness of the heater (mm) (=30 mm), Fig. 1
T	temperature (°C)
ΔT	dimensional temperature difference, Eq. (1) (°C)
z	axial co-ordinate (mm)

Greek symbols

θ	non-dimensional temperature, Eq. (8)
$\Delta\theta$	non-dimensional temperature difference

Subscripts

amb, ∞	ambient
c	critical
e	average of the heater side
MIN	minimum
MAX	maximum
r	quantity pertaining to radial direction
SET	set point
T	total
z	quantity pertaining to axial direction
1	quantity pertaining to inner-zone, Fig. 1(b)
2	quantity pertaining to outer-zone, Fig. 1(b)

Table 1
Sequence of microlithography manufacturing process steps

Step	Operation	Manufacturing processes
1	Substrate preparation	Oxidation, chemical vapor deposition, etc.
2	Surface preparation	Clean, dehydrate, prime, etc.
3	Application of resist	Spin coating, spraying, rolling, dipping, etc.
4	Soft bake	Low temperature cure to dry resist
5	Expose	Align and expose to selectively polymerize the resist
6	Development	Dissolve the un-polymerized resist
7	Visual inspection	Verify accurate image transfer to photo-resist
8	Post-exposure bake	Higher temperature cure to completely dry and polymerize the resist
9	Etch	Surface, oxide, metal, etc.
10	Strip resist	Organic, acid, or plasma ash removal of resist
11	Visual inspection	Verify accurate image transfer to the layer

measured or estimated in terms of the smallest line-width of the patterned feature on the photo-resist [1,2]. The temperature uniformity of the photo-resist and hence the bake-heater surface itself, during the above mentioned PEB plays a key role in determining the uniformity of photo-resist thickness or CD [3,5–7] for subsequent unit processes such as etching, ion-implantation or deposition, leading to a successful (accurate) manufacture of the semiconductor.

Using numerical methods and theoretical scale analysis from first principles, this paper presents a parametric study of an inverse heat conduction problem (IHCP, [8]) on the axi-symmetric model of a disc heater that maintains a given temperature on its top surface (on which the wafer is heated) for a given length of time. A cost-effective two-zone circumferential redistribution of the heat flux at the bottom surface of the heater is studied in detail to counter the two opposing constraints of the problem: the requirement of a minimum possible heater surface ΔT and the fixed heat losses to the surrounding, which is the cause for the ΔT on the heater surface.

2. Temperature uniformity requirement

The baking (heating) process, performed on several occasions (step 4, 8 and after 9 in Table 1) in the microlithography manufacturing of semiconductors, is done by placing the silicon wafer on a heater, usually made of aluminum [9]. Fig. 1(a) shows the axi-symmetric schematic of a 300 mm diameter wafer placed on a disc heater. The photo-chemistry of the chemical bond, hardening or softening of the photo-resist applied on the wafer, is highly sensitive to a set point temperature (T_{SET}) to be reached by PEB, upon which the chemical reaction is triggered (chemical amplification, [4]). The accuracy of the feature dimensions of the semiconductor circuit pattern to be etched on the wafer depends sensitively on the uniformity of these