Investigation of a Novel Rapid Thermal Processing Concept Using an Electro-Optically Controlled Radiation Cavity

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Abstract

We present numerical investigations of a novel technique for reducing the thermal cycle during lamp-heated rapid-thermal processing (RTP). In our concept the reflective reactor-wall surface is replaced by an electro-optically switchable film, which allows efficient heating and subsequent radiative cooling of processed wafers. Our approach provides an efficient solution to ultrashallow junction requirements for forthcoming CMOS generations.

1 Introduction

The principal advantage of RTP is its low thermal budget and reduced process cycle time. In most RTP reactors, wafers are heated by lamp radiation in the red to near-infrared range [1]. The reactor walls are provided with highly reflective metallic coatings to minimize radiative losses. This enables rapid heating up to the set processing temperature, and minimal energy use once this temperature is reached. However, at the end of the thermal cycle the reflective wall presents a disadvantage as it slows the rate of radiative cooling of the wafer. At this stage of the thermal cycle one would actually prefer a heat-absorbing wall to accelerate wafer cooling.

Several attempts have been made to accelerate wafer cooling by changing the optical properties of the RTP chamber [2-4]. One approach is to use a chamber with an *absorptive cavity* [2,3]. This achieves rapid cooling, but an ultrahigh-power lamp (150-300 kW) is needed to counterbalance the increased radiative losses from the wafer during processing. Typical cooling rates for absorbing chambers are reported to be 180 °C/s while the best standard chambers cool at 90 °C/s [2,3].

A reduced thermal cycle, using conventional lamp power, can be achieved by switching the reactor wall from reflective, during heating, to absorptive during cooling. This can be done by mechano-optical switching [4], or electro-optical switching [5,6], the latter being of particular interest as it does not require moving parts. In this paper we present calculations showing the potential benefits of this concept. We consider a wafer radiating inside a symmetrical planar-bounded cavity with variable wall reflectivity. Between the wafer and the wall is a partially

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transparent window (e.g. quartz), which absorbs significantly at wavelengths emitted by the wafer (mid- to far-infrared) thus modifying the impact of the switchable wall. In order to obtain analytical formulas for wafer cooling we make the following approximations, accurate to within a few per cent in the range of wavelengths and temperatures (600-1100 °C) of interest: (1) radiation is the dominant heat-loss process, (2) the wafer is opaque to its emitted infrared radiation, (3) the wafer emissivity is independent of wavelength and temperature, (4) the specific heat of the wafer is independent of temperature, (5) the intermediate window does not significantly reflect or re-emit the radiation from the wafer. Furthermore, since window absorption is not the main concern of this paper, we assume for convenience that this is independent of the infrared wavelength emitted by the cooling wafer.

2 Analysis of radiative cooling

Figure 1 shows schematically a wafer surface with reflectivity ρ, emitting radiation through a partly transmitting window of absorbance a, to a reactor wall with reflectivity r. To determine the net radiant power emitted by the wafer surface at absolute temperature T, consider the effect of the multiple absorption and reflection events that occur before each radiated photon is absorbed, either within the window or at the reactor wall. To do this we note the probabilities of absorption/reflection of the emitted photon at each encounter with a solid (wafer, window or wall), and sum over all possible reflections. The total radiated heat per unit area per second emitted from the surface at absolute temperature T, can then be calculated as

$$dQ/dt = [1\text{-}r\,(1\text{-}a)^2].[1 + \rho r(1\text{-}a)^2 + (\rho r)^2(1\text{-}a)^4 + ...]\;\varepsilon\,\sigma\,T^4. \qquad (1)$$

In Eq. (1), the factor $1\text{-}r\,(1\text{-}a)^2$ is the probability that the photon is absorbed during the first cycle of reflection between wafer and wall (solid arrowed lines in Fig. 1), and the series in square brackets takes into account all possible successive reflections (dashed lines in Fig. 1).

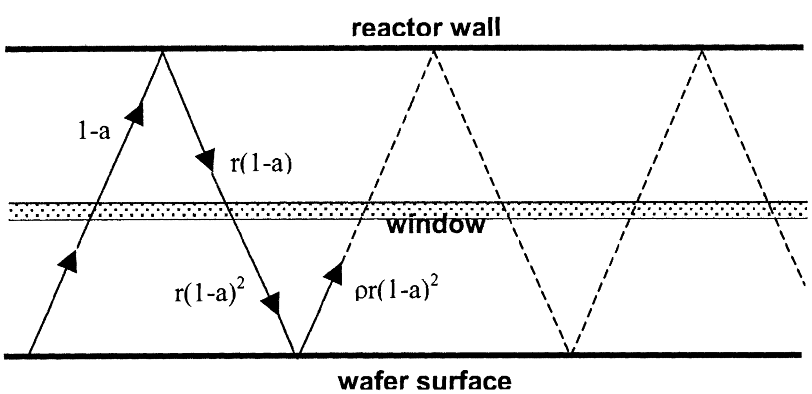

Figure 1: Schematic of radiation transport in the RTP reactor.

Bearing in mind Kirchhoff's law for opaque wafers, $\rho = (1-\varepsilon)$, the formula

$$1 + x + x^2 + x^3 + \ldots = 1 / (1-x)\,, \tag{2}$$

and the relation between the heat capacity and the cooling rate of the wafer,

$$dQ/dt = (dQ/dT)\,.\,(dT/dt) = C_{Si}.\,\rho_{Si}.w\,.\;dT/dt\,, \tag{3}$$

where C_{Si} and ρ_{Si} are the specific heat and density of Si and w is half the wafer thickness (assuming symmetry), we can rewrite Eq. (3) in terms of the cooling rate,

$$dT/dt = -\,\varepsilon\,\{[1-r(1-a)^2] / [1-r\,(1-a)^2(1-\varepsilon)]\}\;\sigma\,T^4 / (C_{Si}\,\rho_{Si}\,w)\,. \tag{4}$$

In a conventional RTP reactor the wall is highly reflecting and impedes wafer cooling. Radiation leaving the wafer has a high probability of being reflected back to the wafer and reabsorbed. If there are no absorbers within the chamber (i.e. a=0), the rate of cooling can be remarkably slow. For example, in the case of 90 % reflectivity, the cooling rate according to Eq. 4 is an order of magnitude slower than would occur in the absence of a reflecting wall. This is much slower than is actually found experimentally in a RTP reactor. If one now allows for a significant amount of absorption in the window, the prediction changes substantially. To illustrate this we consider a typical case where the window (a few mm of quartz) absorbs 20 % of the IR radiation from the wafer on a single pass, corresponding to the value a=0.2.

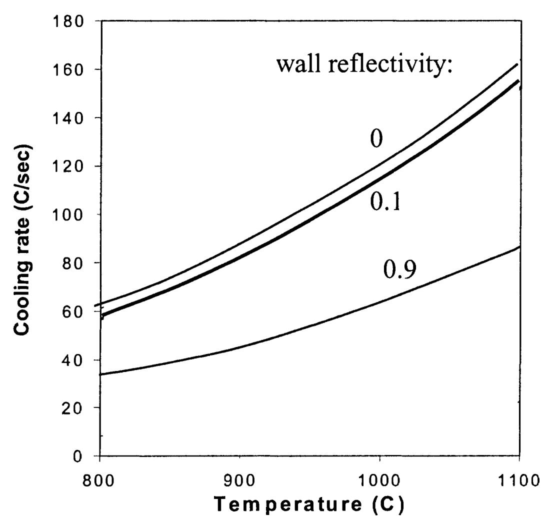

Figure 2: Cooling rate versus temperature for three values of r, with a=0.2, representing the effect of a quartz window between the wafer and the wall.

It is clear from Fig. 2 that, despite the damping effect of window absorption, the rate of cooling is enhanced by a factor of approximately two when the reactor wall is switched from reflective to absorbing. This leads to a significant decrease in thermal budget during 'spike' anneals used to fabricate ultrashallow junctions.

3 Conclusions

The implementation of a switchable-mirror coating for the RTP reactor wall, such that the reflectivity can be reduced to a low value, e.g. 10 %, during wafer cooling, offers approximately a factor of two gain in wafer-cooling rate compared with values reached in conventional lamp-heated RTP reactors. The performance is comparable to that in RTP designs that use high lamp power combined with a passive absorbing wall. The reduction in thermal cycle significantly extends the potential for RTP to form ultra-shallow junctions in forthcoming CMOS generations, while retaining the well-tested lamp-based method of wafer processing.

In order to model the thermal performance of the RTP reactor to a high level of accuracy, a more precise quantitative approach to modelling the cooling part of the RTP cycle may be required in the future. For example, it may become necessary to account for the wavelength dependence of infrared absorption, particularly in the quartz window material, and to consider the detailed reactor geometry. However the simple analysis presented here is a useful guide to the contributions of window and wall absorption to wafer cooling in RTP systems, and it clearly shows the value of the switchable-window approach.

References

[1] Roozeboom F, in *Advances in Rapid Thermal and Integrated Processing*, Roozeboom F (ed.), Kluwer Academic Publishers, Dordrecht, The Netherlands, 1996 pp. 1-34

[2] Fiory A.T., Camm D.M., Lefrançois M.E., McCoy S.P. and. Agarwal A, *Proc. 7th Int. Conf. Advanced Thermal Processing of Semiconductors (RTP'99)*, pp. 273-280

[3] Camm D.M. and Lefrançois M.E., Electrochem. Soc. Symp. Proc. **2000-9** (2000) 429

[4] Bussmann E., German Patent DE 4,142,466 (30 Nov., 1995)

[5] Van der Sluis P., Appl. Phys. Lett. **73** (1998) 1826.; Van der Sluis P. *et al.*, Appl. Phys. Lett. **70** (1997) 3356

[6] Based on U.S. patents 6,047,107 (4 April, 2000) and 6,173,116 (9 Jan., 2001) by Roozeboom F., Duine P.A. and Van der Sluis P; see also Roozeboom F., Van der Sluis P. and Cowern N.E.B., Electrochem. Soc. Symp. Proc. **2001-8** (2001) 41