1-1-1985

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Recommended Citation

C. L. Dym and A. Ballantyne, "Response of Lithographic Mask Structures to Repetitively Pulsed X-rays: Dynamic Response," Journal of Applied Physics, 58 (12), 4726-4729, 15 December 1985. DOI: 10.1063/1.336246

AIP Journal of Applied Physics

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Citation: Journal of Applied Physics **58**, 4726 (1985); doi: 10.1063/1.336246
View online: http://dx.doi.org/10.1063/1.336246
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/58/12?ver=pdfcov
Published by the AIP Publishing

Response of lithographic mask structures to intense repetitively pulsed x rays: Dynamic response analysis

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(Received 11 March 1985; accepted for publication 16 May 1985)

This paper addresses the issue of the dynamic response of thin lithographic mask structures to thermally induced stress fields. In particular, the impact of repetitively pulsed x-ray sources are examined: the short duration (1–100 nsec) pulses induce large step changes in mask temperatures, which can, in turn, induce a dynamic response. The impact of conductive cooling of the mask is to reduce the repetitively pulsed problem to a series of isolated nearly identical thermal impulses of duration approximately equal to the cooling time. The importance of self-weight and prestress is examined, and an analysis of the nonlinear dynamic response to thermal impulses is described.

INTRODUCTION

The use of short duration repetitively pulsed x-ray sources has recently been investigated for development of high throughput x-ray lithographic systems.[1] These sources, such as laser-generated plasma and pinched plasma devices, have pulse durations in the range 1–100 nsec.[2,3] Under such conditions the energy from the pulse is largely deposited in the lithographic mask with no conductive or convective losses to the surroundings. For equivalent average powers, the pulsed source leads to a vastly greater peak mask temperature than a continuous source. Under such circumstances, the thermal stresses in the mask are much greater than for the cw source. This leads to speculation as to the dynamic response of the mask under such a repetitive irradiation.

In particular, we must examine the consequences of mask dynamics upon the achievable resolution and repeatability of mask features. In a companion paper[4] we have examined the consequences of the rapid heating and resultant stresses upon the damage threshold of the mask structure, both for single-pulse and long-term fatigue damage. Thus the companion work (Ref. 4) considers the effect of thermal pulsing on the local (fine grain) response of the substrate, the resist, and their interface, while the present work considers the overall response of a complete mask. The impact of these effects upon x-ray lithographic system design has been described by Hyman *et al.*[5]

Self-weight becomes important for such thin membranes (masks) because the structure does not itself have sufficient bending stiffness to support its own weight. Thus a membrane prestress must be introduced to provide stiffness to support the mask. Furthermore, the very smallness of the thickness-to-radius ratio means that the thermal buckling stress of a clamped circular plate, for example, would easily be exceeded in any lithographic process. This is important because the thermal loading produces a compressive in-plane stress. Hence, thermal effects must be incorporated into the analysis as their presence may significantly reduce the effective stiffness of the mask, leading to excessive dynamic response.

In this paper the formulation of the appropriate mechanics problem is examined first. This is followed by discussions of typical thermal histories for pulsed x-ray lithographic processes and their potential consequences in terms of mask behavior. It is shown that different mask materials may require high prestress in order to avoid excessive sag due to self-weight and to avoid excessive thermal softening.

FORMULATION

The analysis proceeds sequentially through a pair of problems. In the first instance, the nonlinear static response of a thin film to its own weight is examined. Then the nonlinear dynamic response of that membrane to a thermal pulse is analyzed. For axisymmetric isothermal deformation of a statically loaded membrane in plane stress, the equations of equilibrium can be shown to be

$$\frac{d}{dr}(r\sigma_{rr1}) - \sigma_{\theta\theta 1} = 0, \tag{1a}$$

$$\frac{d}{dr}\left[r\sigma_{rr1}\left(\frac{dw_0}{dr} + \frac{dw_1}{dr}\right)\right] + \rho g r = 0, \tag{1b}$$

subject to regularity conditions at the origin ($r = 0$) and boundary conditions at the membrane'e edge ($r = R$):

$$u_1(0) = 0, \quad \frac{dw_0(0)}{dr} = \frac{dw_1(0)}{dr} = 0, \tag{2a}$$

$$(r\sigma_{rr1})_{r=0} = 0,$$

$$w_1(R) = 0, \quad \sigma_{rr1}(R) = \sigma. \tag{2b}$$

Here $w_0(r)$ is an axisymmetric deviation from straightness, $w_1(r)$ is the static response of the first problem, and σ is a tensile prestress applied uniformly around the membrane boundary.

A good approximate solution to the above system of equations is obtained by standard techniques; i.e., use a stress function to satisfy in-plane equilibrium exactly, and an assumed deflected shape to satisfy transverse equilibrium

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and compatibility in the sense of Galerkin.[6] If deflected shapes are assumed in the form

$$[w_0(r),w_1(r)] = h\,\{W_0,W_1\}\left(1-\frac{r^2}{R^2}\right), \tag{3}$$

then transverse equilibrium requires that

$$(\rho g h)(R/h)^2 = 4\sigma(W_0+W_1) + E(h/R)^2(W_1^3+3W_1^2W_0+2W_1W_0^2). \tag{4}$$

Equation (4) defines the load-deflection relationship for an initially imperfect membrane under its own weight (ρgh) and a uniform tensile prestress. For an initially flat membrane, or one that is picked up under tension from a flat surface, $W_0 = 0$ and Eq. (4) reduces to

$$(\rho g h)(R/h)^2 = 4\sigma W_1 + E(h/R)^2 W_1^3. \tag{5}$$

The stresses for the initially flat membrane are

$$\frac{\sigma_{rr1}}{E} = \frac{\sigma}{E}\left(\frac{h}{2R}\right)^2 W_1^2\left(1-\frac{r^2}{R^2}\right), \tag{6a}$$

$$\frac{\sigma_{\theta\theta 1}}{E} = \frac{\sigma}{E}\left(\frac{h}{2R}\right)^2 W_1^2\left(1-3\frac{r^2}{R^2}\right), \tag{6b}$$

This completes the analysis of the first problem. It will be shown below that Eqs. (5) and (6) can sensibly be linearized for thin membranes or masks, even for extremely thin membranes where $(R/h) \gg 1$. The second problem, incorporating the dynamic response of this loaded membrane to a thermal shock applied uniformly over the membrane, is now considered. The solution proceeds quite similarly, the major differences being that the constitutive relations used must reflect the thermal strain,[7]

$$\epsilon_{rr} = \alpha T + (1/E)(\sigma_{rr2} - \nu\sigma_{\theta\theta 2}),$$
$$\epsilon_{\theta\theta} = \alpha T + (1/E)(\sigma_{\theta\theta 2} - \nu\sigma_{rr2}), \tag{7}$$

the initial deflection for the second problem is the result $w_1(r)$ of the first problem, and transverse inertia must be incorporated. In addition, the stress boundary condition at $r = R$ ($\sigma_{rr1} = \sigma$ in the first problem) is replaced with the condition that there is no radial motion in the plane of the membrane; i.e., for axisymmetric deformation,

$$\alpha TE + \sigma_{\theta\theta 2}(R,t) - \nu\sigma_{rr2}(R,t) = 0. \tag{8}$$

For a modal response

$$w_2(r,t) = hW_2(t)\left(1-\frac{r^2}{R^2}\right), \tag{9}$$

the equation of motion follows in the usual fashion:

$$\frac{1}{6}\left(\frac{\rho R^2}{E}\right)\ddot{W}_2 + \left(\frac{\sigma}{E}-\frac{\alpha T(t)}{1-\nu}\right)W_2 + \left(\frac{7-\nu}{3(1-\nu)}\right)(h/R)^2 \times (W_2^3+3W_2^2W_1+2W_2W_1^2) = \frac{p_0(t)}{E}\left(\frac{R}{2h}\right)^2 - \left(\frac{\sigma}{E}-\frac{\alpha T(t)}{1-\nu}\right)W_1. \tag{10}$$

Here $p_0(t)$ is a surface load applied during the second problem phase, and the temperature may also vary over time; i.e., $T = T(t)$.

Before turning to a discussion of the response and implications for thin-film use, two observations are in order. First, Eq. (10) readily yields a very good approximation to the lowest eigenvalue of an isothermally prestressed circular membrane:

$$f = \frac{2.45}{2\pi R}\sqrt{\sigma/\rho} = \frac{2.45}{2\pi}\left(\frac{c_L}{R}\right)\sqrt{\frac{(1-\nu^2)\sigma}{E}}, \tag{11}$$

where c_L is the longitudinal (bar) wave speed, and the "exact" frequency coefficient is 2.404.[3] Secondly, the effect of the applied temperature $T(t)$ is to lower the stiffness—and thus also the natural frequency—of the stretched membrane. This is observed in the linear term of Eq. (10) and is a consequence of the compressive nature of the thermal stress induced by fixing the boundary, as per Eq. (8).

MASK THERMAL HISTORY

The mask is subjected to intense repetitively pulsed x-ray radiation, with a significant fraction of the fluence being absorbed in the mask substrate, and almost all that is incident on the absorber pattern is absorbed. For the short pulse durations of interest (10^{-9}–10^{-7} sec), a nonuniform temperature profile exists through the mask thickness at the end of the pulse. This leads to generation of considerable thermal stresses across the absorber/substrate interface; this is examined in detail in Ref. 4. There is subsequent relaxation of temperature gradients through the mask leading to an essentially uniform temperature ΔT on a timescale of order 10^{-6} sec (Fig. 1). The cooling of the mask is essentially controlled by conduction through to the resist and its substrate. This has been examined by Grobman[8] and Hyman *et al.*[5] and the characteristic timescale for cooling is given by

$$\tau_{\text{cond}} = \frac{\rho c h l}{k_a}, \tag{12}$$

where ρc is the volumetric specific heat, l is the gap distance between mask and resist, and k_a is the thermal conductivity of the helium gas in the chamber. This leads to a temperature history given by

$$T(t) = \Delta T_0 e^{-t/\tau_{\text{cond}}}, \tag{13}$$

where

$$\Delta T_0 = J_0\left(\frac{(e^{h_s/\lambda_s}-1)+\gamma(1-e^{-h_a/\lambda_a})}{(\rho c h)_s+\gamma(\rho c h)_a}\right). \tag{14}$$

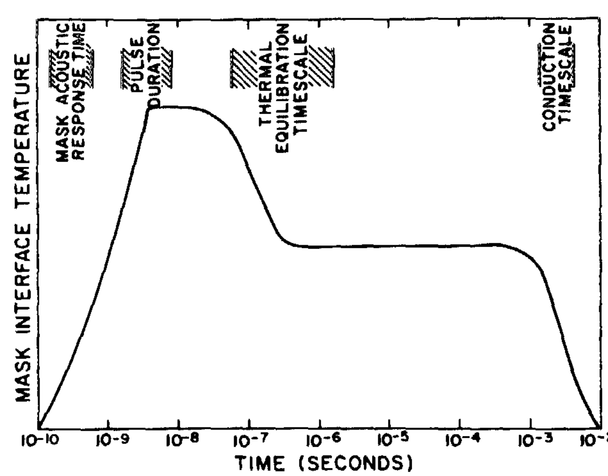

FIG. 1. Mask thermal history.

J_0 is the resist dosage per pulse (fluence), λ_s and λ_a are the radiative absorption depths of substrate and absorber, respectively, and γ is the fraction of the mask area covered by the absorber.

The conductive cooling timescale is illustrated parametrically in Fig. 2 for a silicon substrate. The values for other materials, such as Mylar or silicon nitrite, are not very different from those for silicon. It can be seen that for representative values of mask thickness and gap size, the conduction timescale is of order 10^{-3} sec, which is considerably shorter than the likely repetition frequency interpulse times ($\sim 10^{-2}$ sec). This leads to the conclusion that little thermal energy is stored in the mask between pulses. (For 30-Hz operation this corresponds to $\sim 10^{-4} \Delta T_0$.) Hence the behavior of the mask may be treated as if it is being subjected to a sequence of identical thermal impulses of duration $\sim \tau_{\rm cond}$.

The magnitude of the thermal pulses is illustrated in Fig. 3. The temperature rises shown are for a resist dosage of 10 mJ/cm^2. It can be seen that temperature rises of between 10 and 100 K can be expected, depending upon the specific x-ray wavelength and power distribution. It is shown in Ref. 4 that mask damage thresholds for gold upon silicon substrate are of order 10 mJ/cm^2. For other materials and mask design concepts, the damage fluence may be several times greater.

The effects of these fluence requirements on mask response are explored in the next section.

RESPONSE AND IMPLICATIONS

There are two basic questions of interest in the application of the above model to thin-film structures in microprocessor chip lithography: (1) Is it possible to stretch the membrane so that it remains flat, or very nearly so, under its own weight? (2) Is the reduction in stiffness caused by the thermal loading likely to cause a dynamic response that would not be tolerable or acceptable?

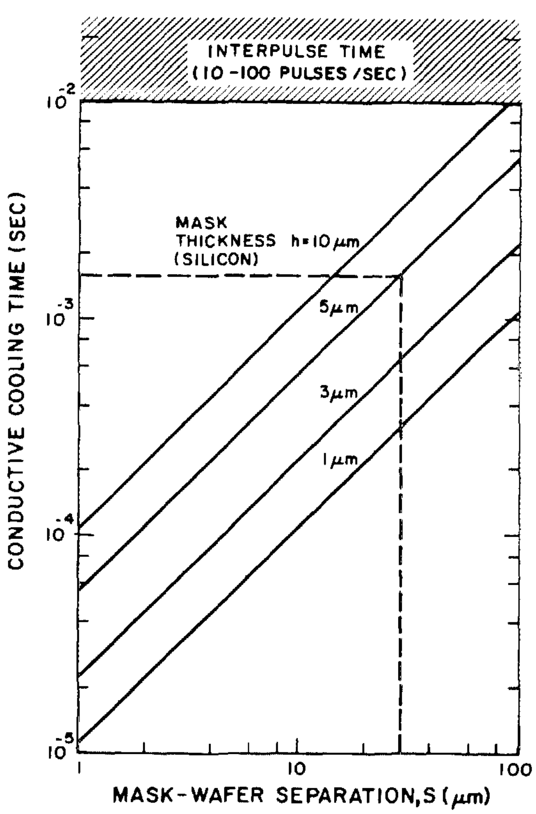

FIG. 2. Conductive heat transfer timescales for silicon substrate as a function of mask-wafer separation.

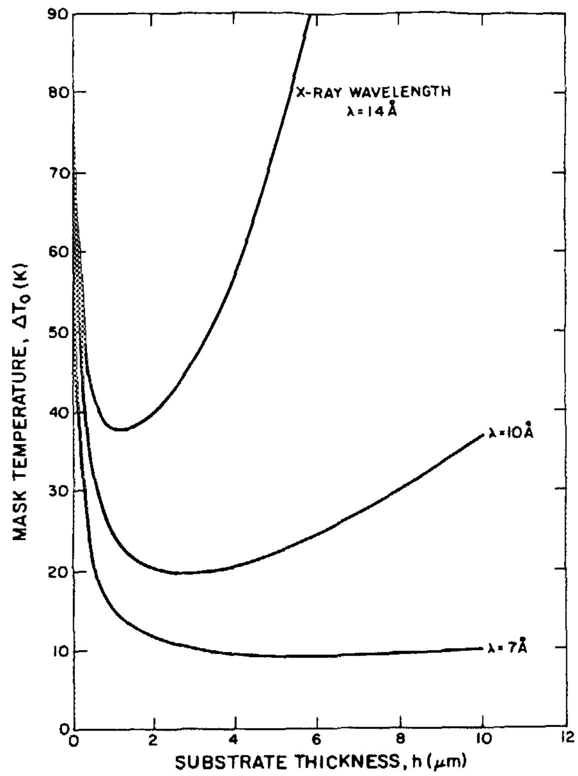

FIG. 3. Mask temperature transient as a function of x-ray wavelength and substrate thickness for a resist dosage of 10 mJ/cm^2.

To investigate the possibility of minimizing the film deflection due to self-weight, require that

$$W_1 = \frac{w_1(0)}{h} = \frac{p}{100} < 1. \tag{15}$$

Thus, p represents the maximum deflection of the membrane in multiples of hundreths of the film thickness. In order for the inequality of Eq. (15) to obtain, from a linearized form of Eq. (5), the following expression for σ must apply:

$$\frac{\sigma}{E} = \frac{25}{(1-\nu^2)p}(gR/c_L^2)(R/h). \tag{16}$$

For a typical silicon mask, $c_L \cong 7.10 \times 10^3$ m/sec, $\nu = 0.30$, $R = 6.35 \times 10^{-2}$ m, and $h = 5.0 \times 10^{-6}$ m, so that

$$(\sigma/E)_{\rm si} \cong \frac{4.31 \times 10^{-3}}{p}, \tag{17a}$$

while for a Mylar mask, $c_L \cong 2111$ m/sec and $\nu = 0.34$, so that

$$(\sigma/E)_{\rm Mylar} \cong \frac{4.88 \times 10^{-2}}{p}. \tag{17b}$$

For a silicon mask, therefore, it is quite reasonable to expect that a realistic prestress can be used to minimize the self-weight deflection, while for Mylar the corresponding prestress requirement might be too high for practical application. In either case, however, substitutions from Eqs. (15)

and (16) can be used to verify the appropriateness of the linearization of Eq. (5).

To assess the effect of temperature on the dynamics of the film, look at the linear fundamental frequency of the equation of motion, Eq. (10). That frequency is

$$f_T \cong \frac{2.45}{2\pi}\left(\frac{\sqrt{1-\nu^2}c_L}{R}\right)\sqrt{\frac{\sigma}{E}-\frac{\alpha T}{1-\nu}}. \tag{18}$$

Let the temperature be a multiple of the buckling temperature of a clamped circular plate[6]; i.e., let

$$T(t) = kT_{\rm cr} = \frac{4k}{3(1+\nu)\alpha}(h/R)^2. \tag{19}$$

Then from Eqs. (11), (16), and (17) it follows that

$$\frac{f_T}{f_{\rm isothermal}} = [1-(4kp/75)(c_L^2/gR)(h/R)^3]^{1/2}. \tag{20}$$

At first glance it may appear from Eq. (20) that the temperature effect is virtually nonexistent for very thin masks. However, it is important to note that while $T_{\rm cr}$ will be small for thin mask, the dosage requirements (Figs. 2 and 3) will require that $T/T_{\rm cr} = k \gg 1$ for many mask materials. For the example geometry used earlier, $T_{\rm cr} \cong (6.20/\alpha)10^{-9}$ °C $\cong 5\times10^{-3}$ °C for both Mylar and silicon masks, but the dosage requirements are such that T(silicon) $\cong$ 30 °C and T(Mylar) $\cong$ 300 °C. Hence k (silicon) $\cong$ 6000 and k (Mylar) $\cong$ 60 000. Thus, for both silicon and Mylar,

$$\frac{f_T}{f_{\rm isothermal}} \cong 1 - 0.01p. \tag{21}$$

Thus some softening due to thermal loading is indicated, and so a proper design for a thin mask must account for the deflection requirement through a choice of the parameter "p" and it must properly assess the correct fluence and temperature requirement for successful etching.

CONCLUSIONS

The impact of high-intensity pulsed x-ray irradiation of lithographic mask structures, in terms of dynamic structural response, are mitigated by conductive cooling to the resist substrate. However, very high pulse repetition frequencies (in excess of several hundred hertz) or poor cooling design (through excessively large mask-resist spacing or low gas pressure) may result in the response not reducing to the single-pulse limit. In such a limiting condition the mask cools between pulses. If this does not occur, the mask temperature may become excessive, inducing possible mask damage or distortion.

The high temperatures generated by the pulses, in combination with effects of self-weight, lead to a requirement of large prestress conditions in the mask. We have demonstrated that a typical metallic mask substrate material, such as silicon, with a realistic prestress, could keep the self-weight deflection within acceptable limits. A polymer material, such as Mylar, may be unable to achieve an acceptably low deflection. Also, there will be some softening of the mask stiffness, leading to a reduction of the fundamental frequency, which may be significant. In combination with high repetition rate this opens up the possibility for structural vibration that may significantly affect the accuracy and distortion of the pattern etched into the resist.

ACKNOWLEDGMENT

We whould like to acknowledge the support of the Rome Development Center, Air Force Systems Command under Contract No. F19628-80-C-0176.

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