UCRL-CR-119635
S/C-B116831

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January 19, 1995

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Fatigue Expectations In A Molybdenum/Silicon Multilayer Under Pulsed Soft X-ray Radiation

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Abstract

The temperature rise in a Mo/a-Si multilayer x-ray reflective film due to radiation absorption is modeled for the first condenser mirror in a projection lithography system such as the one designed by the Advanced Microtechnology Program at LLNL. The radiation load is pulsed at 1000 Hz with a time average intensity of 500mW/cm². This intensity is the expected maximum on the first condenser mirror. The temperature rise is calculated using the integral transform technique. The film is assumed to have the thermal properties of its poorly conducting substrate, yielding a more conservative (higher) temperature estimate. The surface temperature rise is found to range between 35.6°C and 76.3°C. The stress due to this rise is greatest in the molybdenum film and ranges between 73MPa and 166MPa compressive. This fluctuating stress level, however, is believed to be insufficient, by a factor of five or so, to cause fatigue failure of the film.

Introduction

A thin film multilayer x-ray reflective coating may be expected to undergo a rise in temperature due to absorption of a portion of the incident radiation. The coating and substrate will generally have different thermal properties and the temperature will vary in space and time throughout the coating and substrate. Thermal expansion and contraction will result in a cyclic stress state that might cause fatigue failure of the film. It is unlikely that the irradiance used in a soft x-ray projection lithography system will cause failure due to a simple stress overload. However, due to the pulsed nature of the x-ray source to be used in such a system¹, fatigue failure might result at stresses substantially less than the overload or ultimate strength of the multilayer. The objective of this analysis is to determine whether thermal fluctuations are sufficient to induce cyclic stresses sufficient to cause a fatigue failure after many cycles.

Temperature

The film is very thin relative to the substrate and it is assumed that the x-ray irradiance is uniform over the surface of the film. It is also assumed that all outer surfaces of the film and substrate, except for the back surface of the substrate, are perfectly insulated. Therefore spatial variations in temperature occur only through the thickness of the film and substrate, which are assumed to be flat. The partial differential equation of heat conduction is then

$$(1) \quad \frac{\partial}{\partial x} \left[k \frac{\partial T(x,t)}{\partial x} \right] + g(x,t) = \rho C_p \frac{\partial T(x,t)}{\partial t}$$

Here, k is the thermal conductivity, ρ is mass density, C_p is constant pressure specific heat capacity, T is temperature, x is depth measured from the film surface, t is time and $g(x,t)$ is a heat generation function.

The film consists of 40 bilayers of silicon and molybdenum. Each bilayer has 40 angstroms of silicon and 28 angstroms of molybdenum. This film optimally reflects soft x-rays

with a wavelength of 132 angstroms. The substrate is of fused silica. The conductivity is not a continuous function of depth, so the full analytical solution would treat 81 regions of distinct thermal properties. The boundary conditions at each interface would be single valued temperature and continuity of heat flow. Analytical methods exist for any number of layers. The Laplace transform may be applied with respect to time, leaving a system of ordinary differential equations². Determining the coefficients of the transformed solution such that the interfacial and boundary conditions are satisfied requires very lengthy algebra. Transformation back to the time domain then requires contour integration. Green's functions or an Integral transform technique applied to layers of finite thickness results in an eigenfunction and corresponding eigenvalue problem³. The eigenfunctions for flat layers are sines and cosines. Determination of the eigenvalues for 81 layers, however, requires the solution of a very large transcendental equation which must be done numerically. Another method involves the application of the Laplace transform with respect to time and subsequently finding the Green's functions for the transformed problem⁴. The integration of the Green's functions and the contour integration for the inverse Laplace transform must be done numerically. The integrand for 81 layers is difficult to contend with.

An upper bound of the temperature rise in the film can be obtained, however, by assuming the multilayer has the thermal properties of a poorly conducting substrate. Then the temperature rise in only one layer must be calculated. If the multilayer would not fail at this higher estimate of the temperature then the multilayer will not fail by fatigue at the actual temperature achieved. The substrate material assumed in this study is SiO₂. The integral transform technique was used to calculate the temperature.

Integral Transform Solution

The equation to be solved is then

$$(2) \quad \frac{\partial^2}{\partial x^2} T(x,t) + \frac{1}{k} g(x,t) = \frac{1}{\alpha} \frac{\partial}{\partial t} T(x,t) \quad \text{for } 0 \leq x \leq L, t > 0$$

where α is the thermal diffusivity equal to $k/\rho C_p$. The general boundary conditions are

$$(3) \quad -k \frac{\partial T}{\partial x} + h_1 T = f_1(t) \quad x = 0, t > 0$$

$$(4) \quad k \frac{\partial T}{\partial x} + h_2 T = f_2(t) \quad x = L, t > 0$$

where h_1 and h_2 are the convective heat transfer coefficients at $x=0$ and $x=L$ (see Figure 1), and $f_1(t)$ and $f_2(t)$ are nonhomogeneous conditions on the heat transfer. The initial condition is

$$(5) \quad T = F(x) \quad t = 0, 0 \leq x \leq L$$

The integral transform is developed from the solution of the following eigenvalue problem

$$(6) \quad \frac{d^2}{dx^2} X(\beta_m, x) + \beta_m^2 X(\beta_m, x) = 0 \quad 0 \leq x \leq L$$

subject to the homogeneous boundary conditions

$$(7) \quad -k \frac{dX}{dx} + h_1 X = 0 \quad x = 0$$

$$(8) \quad k \frac{dX}{dx} + h_2 X = 0 \quad x = L$$

where $X(\beta_m, x)$ satisfies the orthogonality condition

$$(9) \quad \int_0^L X(\beta_m, x') X(\beta_n, x') dx' = \begin{cases} 0 & m \neq n \\ N(\beta_m) & m = n \end{cases}$$

The temperature can be represented in terms of the eigenfunctions

$$(10) \quad T(x,t) = \sum_{m=1}^{\infty} C_m(t) X(\beta_m, x)$$

$C_m(t)$ is determined by multiplying equation (10) by $X(\beta_m, x)$, integrating with respect to x and utilizing the orthogonality condition

$$(11) \quad C_m(t) = \frac{1}{N(\beta_m)} \int_0^L X(\beta_m, x') T(x', t) dx'$$

Figure 1: The coordinates of the system

This may then be substituted into (10) to obtain

$$(12) \quad T(x, t) = \sum_{m=1}^{\infty} \frac{X(\beta_m, x)}{N(\beta_m)} \left[\int_0^L X(\beta_m, x') T(x', t) dx' \right]$$

This representation is split to define the integral transform pair

$$\text{Transform (13)} \quad \bar{T}(\beta_m, t) = \int_0^L X(\beta_m, x') T(x', t) dx'$$

$$\text{Inversion (14)} \quad T(x, t) = \sum_{m=1}^{\infty} \frac{X(\beta_m, x)}{N(\beta_m)} \bar{T}(\beta_m, t)$$

The transform is applied to (2), removing partial derivatives with respect to x , leaving an ordinary differential equation with respect to time. The transformed solution is found such that the transformed initial condition is satisfied. The inversion formula is then used to obtain the final solution. Applying the transform results in:

$$(15) \quad \int_0^L X(\beta_m, x') \frac{\partial^2 T(x', t)}{\partial x'^2} dx' + \frac{1}{k} \int_0^L X(\beta_m, x') g(x', t) dx' = \frac{1}{\alpha} \frac{\partial}{\partial t} \int_0^L X(\beta_m, x') T(x', t) dx'$$

The last two integrals are the transforms of g and T . Applying Green's theorem to the first integral

$$(16) \quad \int_0^L \left(X \frac{\partial^2 T}{\partial x'^2} - T \frac{\partial^2 X}{\partial x'^2} \right) dx' = - \left[X \frac{\partial T}{\partial x'} - T \frac{\partial X}{\partial x'} \right]_{x'=0} + \left[X \frac{\partial T}{\partial x'} - T \frac{\partial X}{\partial x'} \right]_{x'=L}$$

so that

$$(17) \quad \int_0^L X \frac{\partial^2 T}{\partial x'^2} dx' = \int_0^L T \frac{\partial^2 X}{\partial x'^2} dx' - \left[X \frac{\partial T}{\partial x'} - T \frac{\partial X}{\partial x'} \right]_{x'=0} + \left[X \frac{\partial T}{\partial x'} - T \frac{\partial X}{\partial x'} \right]_{x'=L}$$

Since the eigenvalues β are discrete, the derivatives of the eigenfunctions with respect to x are total derivatives. Utilizing (6) and the definition of the transform

$$(18) \quad \int_0^L T \frac{\partial^2 X}{\partial x'^2} dx' = -\beta_m^2 \bar{T}(\beta_m, t)$$

The boundary conditions are used to evaluate the bracketed terms. Multiplying (3) and (4) by

$X(\beta_m, x)$ and (7) and (8) by $T(x, t)$, then subtracting (7) from (3) and (8) from (4) leaves

$$(19) \quad -k \left[X \frac{\partial T}{\partial x'} - T \frac{dX}{dx'} \right]_{x'=0} = X_{x'=0} f_1(t) \quad \text{and} \quad k \left[X \frac{\partial T}{\partial x'} - T \frac{dX}{dx'} \right]_{x'=L} = X_{x'=L} f_2(t)$$

so that

$$(20) \quad \int_0^L X \frac{\partial^2 T}{\partial x'^2} dx' = -\beta_m^2 \bar{T} + \frac{X f_1}{k} \Big|_{x'=0} + \frac{X f_2}{k} \Big|_{x'=L}$$

The transformed differential equation is then

$$(21) \quad \frac{d\bar{T}(\beta_m, t)}{dt} + \alpha \beta_m^2 \bar{T}(\beta_m, t) = A(\beta_m, t)$$

where

$$(22) \quad A(\beta_m, t) = \frac{\alpha}{k} \bar{g}(\beta_m, t) + \alpha \left[\frac{X(\beta_m, x)}{k} \Big|_{x=0} f_1(t) + \frac{X(\beta_m, x)}{k} \Big|_{x=L} f_2(t) \right]$$

For the case where the temperature is directly specified at a boundary, for example at $x=L$;

multiply (4) by $\frac{dX}{dx}$ and (8) by $\frac{\partial T}{\partial x}$, and then subtract (4) from (8). This yields:

$$(23) \quad \text{replace } \frac{X(\beta_m, x)}{k} \Big|_{x=L} \text{ with } -\frac{1}{h_2} \frac{dX(\beta_m, x)}{dx} \Big|_{x=L}$$

in (22). The initial condition must also be transformed:

$$(23) \quad \bar{F}(\beta_m) = \int_0^L X(\beta_m, x') F(x') dx' \quad t = 0$$

The solution satisfying (21) and (23) is

$$(24) \quad \bar{T}(\beta_m, t) = \exp(-\alpha \beta_m^2 t) \left[\bar{F}(\beta_m) + \int_0^t \exp(\alpha \beta_m^2 t') A(\beta_m, t') dt' \right]$$

Inverting this gives the solution

$$(25) \quad T(x, t) = \sum_{m=1}^{\infty} \frac{X(\beta_m, x)}{N(\beta_m)} \exp(-\alpha \beta_m^2 t) \left[\bar{F}(\beta_m) + \int_0^t \exp(\alpha \beta_m^2 t') A(\beta_m, t') dt' \right]$$

Specific Solution

The substrate is assumed to be 1cm thick. The x-ray source is modeled as in ref. 1, with radiation pulses of constant intensity, and one nanosecond duration occurring at a frequency of 1000Hz. Thus the intensity is assumed to be at full strength over the duration of the pulse. The reflectivity of the film is ~60%, but only for a narrow range of wavelength. Since the irradiance on the first condenser optic will be broad-band relative to this range, it will be conservatively assumed that all the energy is absorbed. Use of computer modeling⁵ to calculate the absorption profile in the multilayer showed a complex profile within an exponentially decreasing upper bound. The complexity is quasiperiodic with a period equal to the bilayer thickness. It can be expected, however, that the conversion of the photons to thermal energy will occur over a volume on the order of the bilayer thickness. Thus it may be assumed that the heat generation function, $g(x,t)$, varies in space as $\exp(-\eta x)$. The value of η found for the absorption profile calculated for the desired wavelength, 1.9×10^5 /cm, was taken as an average of all wavelengths. The time averaged intensity on the first condenser optic was taken to be 500mW/cm², as estimated in ref. 1. The heat source then is

$$(26) \quad g(x,t) = G \exp(-\eta x) q(t) \quad q(t) = \begin{cases} 1 & n\tau_0 < t < n\tau_0 + \tau_1 \\ 0 & n\tau_0 + \tau_1 < t < (n+1)\tau_0 \end{cases}$$

where τ_0 is the period between the beginning of pulses and τ_1 is the pulse duration. The energy delivered per pulse per period τ_0 must equal the time averaged intensity:

$$(27) \quad \left[\int_0^L G \exp(-\eta x') dx' \cdot \tau_1 \right] \left[\frac{1}{\tau_0} \right] = [\theta]$$

$$G \left(\frac{-1}{\eta} \exp(-\eta x) \right) \Big|_0^L = \frac{\tau_0}{\tau_1} \theta \quad \rightarrow \quad G \equiv \frac{\tau_0}{\tau_1} \eta \theta \quad \text{for } \eta L \gg 1$$

θ is intensity. The top of the film is exposed to vacuum so

$$(28) \quad \left. \frac{\partial T(x,t)}{\partial x} \right|_{x=0} = 0$$

The temperature of the back of the substrate is assumed to be fixed at zero. Therefore,

$$(29) \quad T(x,t)|_{x=L} = 0$$

The eigenfunctions and eigenvalues for this case are

$$(30) \quad X(\beta_m, x) = \cos(\beta_m x) \quad \beta_m = \frac{(2m-1)\pi}{2L} \quad m = 1, 2, 3, \dots$$

The initial condition is taken to be $T=0$. The solution is then

$$(31)$$

$$T(x,t) = \frac{2}{L} \sum_{m=1}^{\infty} \exp(-\alpha\beta_m^2 t) \cos(\beta_m x) \frac{\alpha}{K} \int_0^t \exp(\alpha\beta_m^2 t') q(t') \int_0^L \frac{\tau_0}{\tau_1} \eta / \exp(-\eta x') \cos(\beta_m x') dx' dt'$$

The integral with respect to x is

$$(32) \quad \int_0^L \exp(-\eta x') \cos(\beta_m x') dx' = \frac{\exp(-\eta L) \beta_m (-1)^{m+1} + \eta}{\eta^2 + \beta_m^2}$$

Integration with respect to t depends on whether a radiation pulse is currently on or not.

During a pulse N,

$$(33) \quad \int_0^t \exp(\alpha\beta_m^2 t') q(t') dt' = \sum_{n=0}^{N-1} \int_{n\tau_0}^{(n+1)\tau_0} \exp(\alpha\beta_m^2 t') dt' + \int_{N\tau_0}^{N\tau_0+t''} \exp(\alpha\beta_m^2 t') dt'$$

$$N\tau_0 + t'' = t \quad 0 < t'' < \tau_1$$

$$= \frac{1}{\alpha\beta_m^2} (\exp(\alpha\beta_m^2 \tau_1) - 1) \sum_{n=0}^{N-1} \exp(\alpha\beta_m^2 n\tau_0) + \frac{1}{\alpha\beta_m^2} \exp(\alpha\beta_m^2 N\tau_0) (\exp(\alpha\beta_m^2 t'') - 1)$$

Multiplying through by the exponential factor that is outside the integral in (31) gives

$$(34) \quad \frac{(\exp(\alpha\beta_m^2 \tau_1) - 1) \exp(-\alpha\beta_m^2 t'')}{\alpha\beta_m^2} \sum_{n=0}^{N-1} \exp(-\alpha\beta_m^2 (N-n)\tau_0) + \frac{1}{\alpha\beta_m^2} (1 - \exp(-\alpha\beta_m^2 t''))$$

Note that

$$(35) \quad \sum_{n=0}^{N-1} \exp(-\alpha\beta_m^2(N-n)\tau_0) = \sum_{n=1}^N \exp(-\alpha\beta_m^2 n\tau_0) = \sum_{n=1}^N (\exp(-\alpha\beta_m^2 \tau_0))^n$$

It is fatigue behavior that is of interest, so utilizing the Geometric Series Theorem for long times

$$(36) \quad \lim_{N \rightarrow \infty} \sum_{n=j}^N r^n = \frac{r^j}{1-r} \quad |r| < 1$$

gives

$$(37) \quad \sum_{n=1}^{\infty} (\exp(-\alpha\beta_m^2 \tau_0))^n = \frac{\exp(-\alpha\beta_m^2 \tau_0)}{1 - \exp(-\alpha\beta_m^2 \tau_0)}$$

Combining it all gives the temperature during a pulse long after start-up

$$(38) \quad T(x,t) = \frac{2\tau_0\eta\theta}{L\tau_1 k} \sum_{m=1}^{\infty} \cos(\beta_m x) \left(\frac{\exp(-\eta L)\beta_m(-1)^{m+1} + \eta}{\beta_m^2(\eta^2 + \beta_m^2)} \right) \cdot \left(\frac{1 - \exp(-\alpha\beta_m^2 t'')(1 - \exp(-\alpha\beta_m^2(\tau_0 - \tau_1))) - \exp(-\alpha\beta_m^2 \tau_0)}{1 - \exp(-\alpha\beta_m^2 \tau_0)} \right)$$

$0 < t'' < \tau_1$

Similar calculations give the temperature between pulses

$$(39) \quad T(x,t) = \frac{2\tau_0\eta\theta}{L\tau_1 k} \sum_{m=1}^{\infty} \cos(\beta_m x) \left(\frac{\exp(-\eta L)\beta_m(-1)^{m+1} + \eta}{\beta_m^2(\eta^2 + \beta_m^2)} \right) \cdot \left(\frac{\exp(-\alpha\beta_m^2(t'' - \tau_1)) - \exp(-\alpha\beta_m^2 t'')}{1 - \exp(-\alpha\beta_m^2 \tau_0)} \right)$$

$\tau_1 < t'' < \tau_0$

The material properties of molybdenum, amorphous silicon, and polycrystalline silicon dioxide are shown in table 1^(ref).

Table 1

	Mo	a-Si	SiO ₂
mass density	10.2 g/cm³ ⁽⁶⁾	2.3 g/cm³ ⁽¹⁾	2.2 g/cm ³ ⁽¹⁾
specific heat capacity	0.25 J/g-K ⁽⁶⁾	0.71 J/g-K ⁽¹⁾	0.74 J/g-K ⁽¹⁾
thermal conductivity	1.4 W/cm-K ⁽⁶⁾	1.49 W/cm-K ⁽¹⁾	0.014 W/cm-K ⁽¹⁾
coefficient of thermal expansion	5.0 ppm/K ⁽⁷⁾	2.8 ppm/K ⁽⁷⁾	0.55 ppm/K ⁽¹⁾
biaxial elastic modulus	460 GPa ⁽⁷⁾	140 GPa ⁽⁷⁾	

Note: Bold type indicates bulk values where film values could not be found. Substrate assumed rigid, so elastic modulus of SiO₂ not required.

It can be seen that the conductivity of SiO₂ is much less than that of the film materials.

The peak temperature rise, which occurs at the end of a pulse, is shown in Figure 2. The peak surface temperature rise is 76.3°C. The temperature rise at the onset of a pulse was found to be 35.6°C. A numerical solution for the surface temperature of a substrate is plotted in reference 1. The numerical solution for the substrate temperature was said to follow a scaling law¹

$$(40) \quad T_{sub,new} = T_{sub,old} \frac{(new\ thickness)(new\ load)}{(old\ thickness)(old\ load)} \cdot \frac{(old\ conductivity)}{(new\ conductivity)}$$

Applying (40) to the solution plotted in reference 1 assuming a silicon dioxide optic that is 1cm thick and irradiated at 500mW/cm² results in a baseline temperature rise of 38.8°C with excursions to 44.2°C. The irradiation of 500mW/cm² is the estimated maximum on the first condenser mirror¹. The difference in the two solutions may be due to absence of heat generation within the material for the numerical solution.

Stress and Fatigue

The lateral dimensions of a thin film are essentially constrained by a thick substrate⁸. The axial stress within the film plane due to heating in any layer of the film is then, approximately

$$(41) \quad \sigma_l = E_l(\phi_{sub}\Delta T_{sub} - \phi_l\Delta T_l)$$

Figure 2: Maximum temperature rise in
a film with substrate conductivity

where σ is stress, E is biaxial elastic modulus, ϕ is coefficient of thermal expansion, and ΔT is temperature rise, l refers to layer, and sub refers to substrate. The thermal component of stress in the hottest molybdenum layer ranges from 73MPa compressive to 166MPa compressive. In the hottest silicon layer it ranges from 11MPa compressive to 27MPa compressive. The residual stress in the sputter deposited molybdenum thin film in the multilayer is tensile (~ 1400 MPa) and greater than the fracture stress of the bulk material⁹. These were for silicon substrates, rather than fused silica, but residual stress measurements indicate comparable stresses for fused silica¹². The magnitude of the stress in the molybdenum indicates that the material has yielded without fracture or that dislocation formation and/or motion is highly inhibited in a thin (≈ 20 angstrom) film. Our experiments indicate that the formation of misfit dislocations may be inhibited; as films of this thickness often are absent of misfit dislocations¹³ and that our annealing experiments indicate creation of these dislocations only after thermal activation. Fatigue crack initiation requires some level of plasticity along slip bands in some grains of the material. If it is the case that dislocations are suppressed in thin films so that the normal tensile strength is exceeded, then it is unlikely that the level of thermal stress predicted would cause failure, since dislocation activity is required for fatigue. If plasticity has occurred; the stress amplitude is ± 47 MPa, at 47MPa below the yield stress of the Mo layer. This is about $\pm 3\%$ of the yield stress σ_y , a very low stress amplitude. The silicon is amorphous and so has no dislocations, also the residual stress state is compressive. So fatigue in the silicon layers is irrelevant.

The fatigue limit of bulk Mo is high, about 70% of the yield stress¹⁰, so that the low stress amplitudes in the multilayer are not expected to cause fatigue failure. In the multilayer case, the mean stress σ_m is high (in the above, bulk, case σ_m is zero) at $\sigma_m \cong \sigma_y$. By the Gerber relation¹¹:

$$(42) \quad \sigma_{fl,(\sigma_m \neq 0)} = \sigma_{fs,(\sigma_m = 0)} \left\{ 1 - \left(\frac{\sigma_m}{\sigma_{uts}} \right)^2 \right\}$$

$$\sigma_y \cong 0.9\sigma_{uts} \quad \sigma_m = \sigma_y$$

so that

$$\sigma_{fl,(\sigma_m \neq 0)} = \sigma_{fs,(\sigma_m = 0)} \left\{ 1 - \left(\frac{0.9\sigma_y}{\sigma_y} \right)^2 \right\}$$

$$(43) \quad \sigma_{fl,(\sigma_m \neq 0)} = 0.19(0.7\sigma_{uts})$$

$$\cong 0.15\sigma_y$$

This suggests that even for the high mean stress case of the multilayer, the fatigue limit should be 15% of the residual stress level (the level of work hardening for a dislocated metal); or five times as large as the cyclic stress in the worst case mirror. Considering that the thermal stresses were conservatively calculated, the "margin of safety" in the first condenser mirror, the "worst-case" mirror, is particularly high.

Conclusions

In the first condenser mirror, the most strongly irradiated mirror, the fluctuating thermal stresses are small and appear insufficient to cause fatigue, even considering the high level of residual stress observed in Mo/Si multilayers.

References

1. A.M. Hawryluk and N.M. Ceglio, "Power Loading Limitations in Soft X-ray Projection Lithography", Lawrence Livermore National Laboratory, Report No. UCID.
2. H.S. Carslaw and J.C. Jaeger, *Conduction of Heat in Solids*, 2nd. ed., Clarendon Press, Oxford, 1959.
3. M.N. Ozisik, *Heat Conduction*, John Wiley and Sons, New York, 1980.
4. M.R. Madison and T.W. McDaniel, "Temperature Distributions in an N-Layer film Structure by Static or Scanning Laser or Electron Beam with Application to Magneto-Optical Media", *J. Appl. Phys.* 66 (12), 15 December 1989, 5738-5748.
5. Software Developed by D.G. Stearns, Lawrence Livermore National Laboratory, June 1991.
6. *CRC Handbook of Chemistry and Physics*, 68th ed., CRC Press, 1987.
7. R.R. Kola, D.L. Windt, W.K. Waskiewicz, B.E. Weir, R. Hull, G.K. Celler, C.A. Volkert, "Stress Relaxation in Mo/Si Multilayer Structures", *Appl. Phys. Lett* 60 (25), 22 June 1992, 3120-3122.
8. P.H. Townsend, D.M. Barnett, T.A. Brunner, "Elastic Relationships in Layered Composite Media with approximation for the Case of Thin Films on a Thick Substrate", *J. Appl. Phys.* 62 (11) 4438-4444.

9. R.S. Rosen, D.G. Stearns, M.E. Kassner, J-I Koike, Y. Cheng, S.P. Vernon,
"Kinetics of Interlayer Growth and Changes in Residual Elastic Strain During Annealing,
of Mo/Si Multilayers", manuscript in preparation.
10. *Atlas of Fatigue Curves*, H.E. Boyer ed. ASM, 1986.
11. S. Suresh, *Fatigue of Materials*, Cambridge Press, Cambridge 1991.
12. D.G. Stearns, S.L. Baker, "Substrate Recovery of Mo/Si Multilayer Coated Optics", To be
published in *OSA Proceedings on Soft X-ray Projection Lithography*, edited by A.M.
Hawryluk and F. Zernike.
13. W.D. Nix, *Metall. Trans*, vol 20A ,1989, 2217.