Lithographic modeling speeds thin-film-head development

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MODELING ACCURATELY PREDICTS THE BEHAVIOR OF THICK PHOTORESISTS USED FOR MAKING THIN-FILM HEADS

hin-film heads are produced using planer techniques that are quite similar to those used in manufacturing integrated circuits [1]. From a lithographic standpoint, the thick photoresists (up to 40 mm) and large aspect ratios (up to 6:1) of thin-film heads pose a considerable challenge, which will most likely increase in the years ahead as drive makers attempt to boost head performance by narrowing track widths and pole gaps. The latter will allow more bits to be stored per unit length of track, while the former will increase track density [2].

There's a catch, though. As individual transition regions shrink in size, more copper coils are required so heads can read the magnetic data embedded in the media. More coils increase the structural height of the head, which will require thicker layers of photoresists to process the thin-film head [1,3].

Indeed, many of the critical issues in thin-film-head fabrication directly involve the lithographic process. The dimensions of the copper coils and poles must be carefully controlled since they can affect head performance. However, the large topography of a typical head requires thick photoresist films and long exposure times, resulting in a loss of line-width control [4]. Steep slopes in a thick photoresist film also reduce critical dimension control. And the high reflectivity of the plated metal film can affect critical dimension control by triggering a standing wave.

In the face of these tribulations, lithographic simulation may prove to be the wisest course. There are several software programs that simulate photoresist chemistry under varying optical and exposure conditions to predict the line width and shape of the resist patterns. The semiconductor industry, for example, uses lithographic modeling to trim development time and to help better understand complex problems. For example, broadband i-line lithography [5] and deep UV excimer lithography [6] have been simulated using a software program called PROLITH/2. These semiconductor processes involve substantially smaller geometries and thinner photoresist films than thin-film-head processes. However, the photoresist aspect ratio (i.e., height to line width) for thin-film heads is actually larger than the aspect ratio used in chip making, suggesting that the lithographic challenges are just as great for thin-film heads. Clearly, the thin-film-head industry can benefit from process modeling as much as the semiconductor industry.

For more than a dozen years, lithographic modeling has been used to simulate the processes of image formation, exposure, and development. When properly used, simulation can accurately predict the resulting photoresist profiles for a large range of pho-

INPUT PARAMETERS FOR LITHOGRAPHIC SIMULATION

Imaging tool:	**CEL or Top ARC:**
Wavelength = 420.0 nm	Not used
Bandwidth = 50.0 nm	**Intermediate layers:** None
Numerical aperture = 0.24	**Substrate:** Silicon
Reduction ratio = 1.0	
Image flare = 0.00	**Resist system:** Positive
Aberrations: None	Thickness = 10.000 µm
Partial coherence = 0.85	Absorption parameter, A = 0.35 1/µm
Line width = 4.00 µm	Absorption parameter, B = 0.020 1/µm
Pitch = 8.00 µm	Exposure rate const. C = 0.012 cm^2/MJ
Mask bias = 0.0 µm	Refractive index = 1.670
Focal position = -3.00 µm	Development model: Original Mack
	Max develop rate = 80.0 nm/s
Exposure energy = 500.0 MJ/cm^2	Min develop rate = 0.3 nm/s
	Threshold, M = 0.1
PEB diffusion length = 70.0 nm	Selectivity parameter, n = 2.10
	Relative surface rate = 0.010
Development time = 60.0 sec	Inhibition depth = 1.00 µm

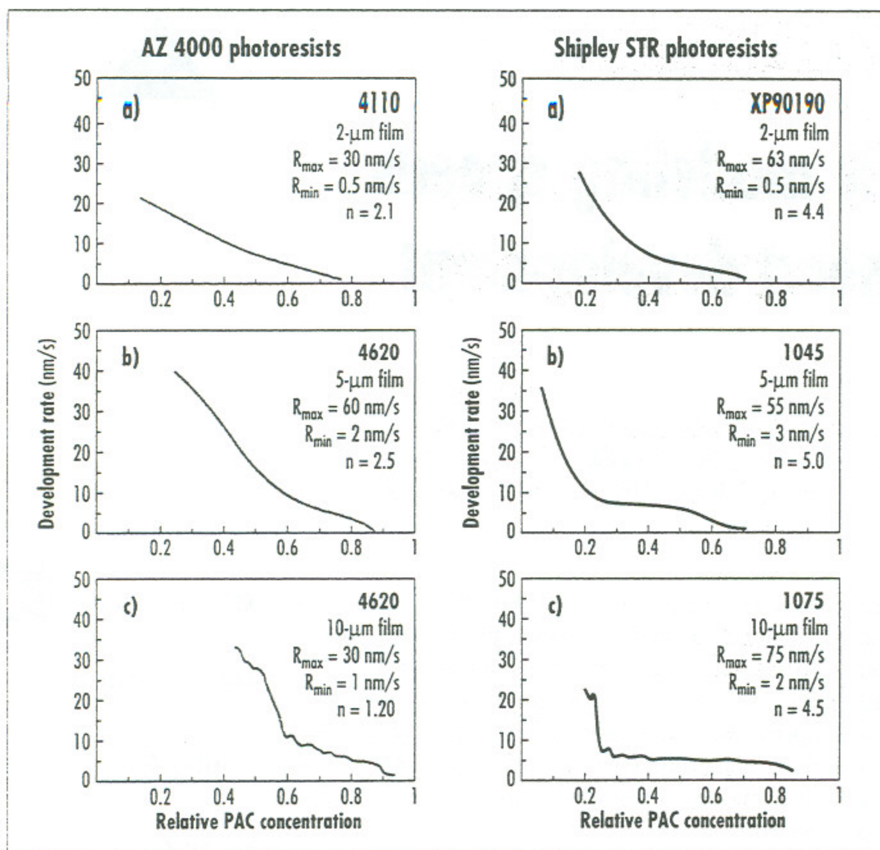

Figure 1. Measured development rates versus relative PAC concentrations for Hoechst Celanese AZ 4000 (left) and Shipley STR (right) photoresists at film thicknesses of (a) 2 μm, (b) 5 μm, and (c) 10 μm. Development rate parameters determined through regression analysis are listed in the upper right corner of each graph.

tolithographic processes, including those used for thin-film-head manufacturing.

Lithography modeling began in the 1970s when researchers at IBM first attempted to characterize the behavior of photoresists. Since that time, much effort has gone into understanding the physics and chemistry of photolithography.

Today, lithographic simulation uses well-tested physical models. The simulation can be performed on a desktop PC or in a workstation using commercial software. Simulation programs require the input of lithographic parameters such as mask feature size, numerical aperture of the stepper lens, the type of resist used, exposure dose, and development time. With proper input parameters, simulation programs can accurately predict the resist line width, side-wall angle, loss, depth of focus, and other pertinent metrics associated with the lithographic process.

Through lithographic modeling photo engineers can perform many "experiments" quickly and at very low cost, using only a few test wafers. Indeed, as thin-film head lithography becomes more complex, sending processing costs through the roof, modeling will gain an irresistible appeal.

One of the keys to simulation is the availability of accurate input parameters. A typical set of input parameters for a lithographic simulation program is listed in the table. Many of the parameters either are known (e.g., exposure wavelength) or are easily obtainable (e.g., stepper partial coherence). For best results, resist/developer properties must be known.

DISSOLUTION BEHAVIOR

Photoresist dissolution has been extensively studied for thin-film photoresist applications [7]. However, how well existing thin-film models apply to the behavior of thick photoresist films is unclear. Thus, the first step is to measure the dissolution behavior of the resists at different thicknesses. If the development model adequately describes the dissolution behavior of the resist, the full lithographic simulator can be used and compared with actual lithographic results.

Two commercial photoresist products, Hoechst Celanese's AZ 4000 and Shipley's STR 1000, were examined for their development rate behavior and photoresist profiles through focus. Both materials are specifically designed for thick photoresist applications. 4620, a high-viscosity formulation of the AZ series, was used to study 5- and 10-μm-thick regimes, while P4110 was used in 2-μm-thick processes. A high-viscosity formulation of the STR series, 1075 (44% solids), was used to study a 10-μm-thick regime, while other Shipley formulations (1045 and XP90190) were used to study 5-μm and 2-μm-thick regimes, respectively.

An Ultratech Stepper model 1500 was used in all experiments. Projection optics, based on a Wynne-Dyson-Hershel 1X lens, provided broadband illumination of the *g* and *h* mercury lines (including the continuum from 390 to 450 nm). The numerical aperture was set at 0.24 for all tests; partial coherence was fixed at 0.85. The Hoechst Celanese photoresist was heated (i.e., "soft baked") in a convection oven at 105°C for 45 minutes, while the Shipley photoresist was heated on a hot plate to 100°C for 90 seconds.

The development rate of the two photoresists was measured at three different thicknesses (2, 5, and 10 μm), using standard open frame, dose-to-clear methods (contrast curves). A range of exposures (50 to 650 MJ/cm^2, in increments of 15 MJ) were used in all tests. Development times were set between 1 and 4 minutes for 2-μm-thick photoresist films; between 2 and 8 minutes for 5-μm-thick films; and between 3 and 12 minutes for 10-μm-thick films.

Photoresist development rates were then calculated for each exposure energy. Based on these rates, an effective average development rate was established for a given film thickness and exposure dose. A corresponding average photoactive compound (PAC) concentration was determined for the various exposure energies and film thicknesses. Photoresist development rate versus relative PAC is shown in Figure 1 for both AZ 4000 and Shipley STR 1000 photoresists. A development rate model was then fit to this experimental data [8], viz:

$$Rate = R_{max}(1 - e^{-EC})^n + R_{min}$$

where R_{max} is the maximum development rate of fully exposed photoresist; R_{min}, the unexposed development rate; n, the developer selectivity; E, the exposure dose; and C, the effective photoresist rate constant.

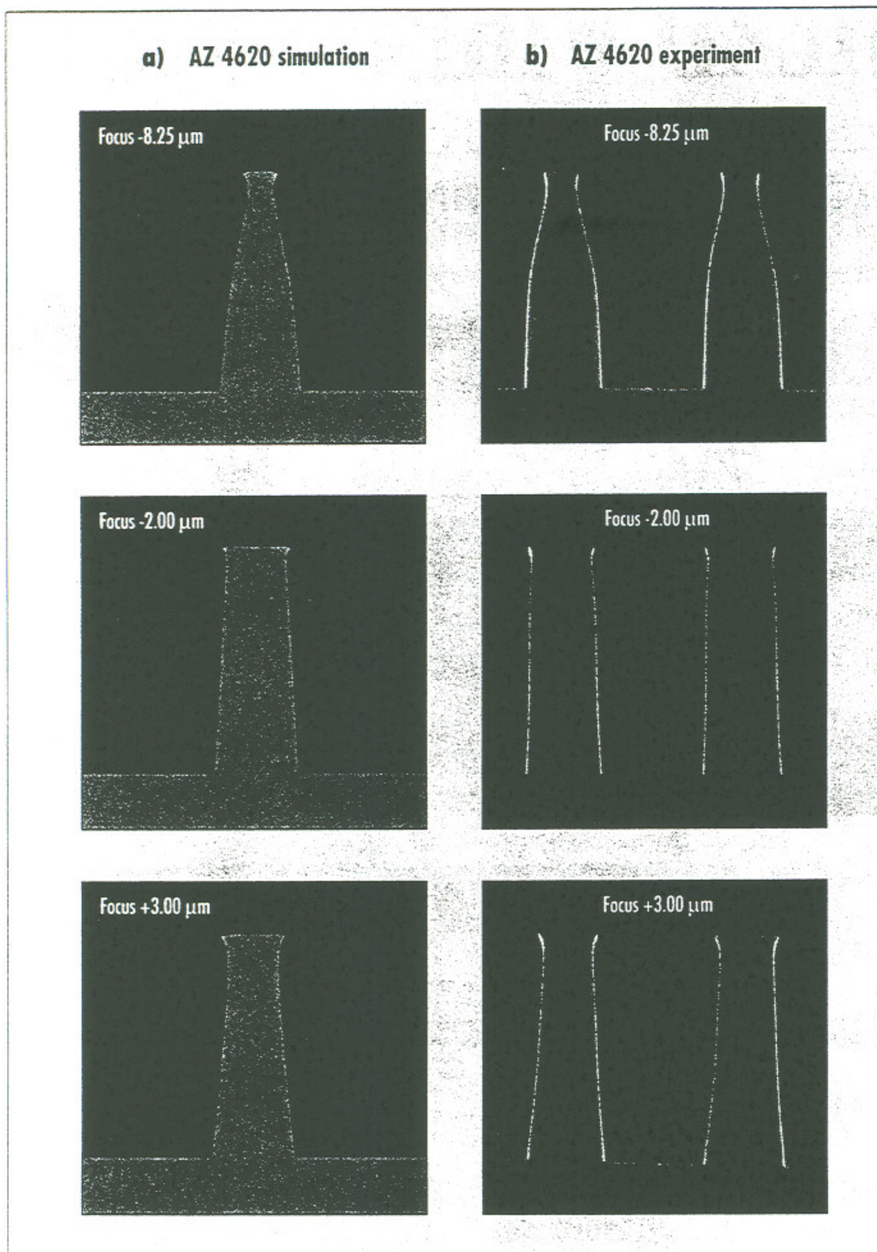

Figure 2. The effect of focus on the resist profile shape under a 10-µm-thick coating of Hoechst Celanese AZ 4620 photoresist. Simulated profiles are to the left of actual resist profiles.

The term e^{-EC} is approximately equivalent to the relative PAC concentration; hence, this equation can be fit to the experimental results to determine development rate parameters. The maximum development rate, R_{max}, for the AZ 4000 family was on the order of 30 to 60 nm/s; for the STR 1000 family, it was slightly higher, around 60 to 75 nm/s.

One notable difference between the two photoresist families is their dissolution selectivity, or n value, which is related to the photoresist contrast. The STR 1000 photoresist exhibits n values of approximately 4.5 to 5.0, while the AZ 4000 photoresist has n values of 1.2 to 2.5. The higher the n value, the greater the exposure and focus latitude.

A scanning electron microscope was used to evaluate a pattern of lines and spaces in the photoresists as a function of focal depth. The results indicate that the STR 1075 photoresist provides better control over a larger focal range than the AZ 4620 photoresist. These results were also predicted in the simulation studies, which pinpointed the relative importance of the developer selectivity, n, in lithographic performance. All in all, the simulation results closely matched the experimental results over a wide range of focal depths (see Figure 2).

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