

Dispelling the Myths about Dyed Photoresist

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Absorption theory is applied to a diazo-type positive photoresist with and without a dye additive. Absorption parameters are measured for both commercially available and experimental dyed resists. The effects of absorption on the standing waves are determined rigorously and observed results are explained. Linewidth control for dyed resists is investigated. Finally, the drawbacks of dyed resists, increased exposure time and sloped resist sidewalls, are discussed.

When light passes through a thin film coated on a reflecting substrate, a standing wave is produced within the film. For the case of photoresist exposure this standing wave effect has been well documented [1-4]. As the dimensions of the lithographic images become very small, standing waves can significantly degrade the resulting photoresist pattern. Thus, an active area of research in recent years has been the reduction of the standing wave effect [5-8]. Various methods have been used to reduce the standing wave pattern, the most common being the post-exposure bake (PEB) [5,6]. This bake is thought to cause a diffusion of the photoactive compound within the exposed photoresist which "smooths out" the standing wave latent image before the resist is developed. A disadvantage of this method is the use of an additional processing step (baking the resist), as well as the added complications of resist decomposition during the bake [9]. An alternate method is the use of an antireflective coating (ARC) [7,8]. This coating decreases the reflectivity of the substrate and thus reduces the standing wave intensity. It has the disadvantage that extra processing steps may be required to deposit, bake or remove the ARC.

A third alternative is to add an absorbing non-bleachable dye to the photoresist [10-18]. This idea was introduced by Neureuther and Dill in 1974 as a method of reducing the effects of standing waves on aluminum substrates [10]. This work remained largely unnoticed and dyed resists were not given much attention for the next ten years. In 1984, Stover, Bol and coworkers, investigating the performance of conventional resists in an i-line stepper, simulated i-line exposure of photoresist by performing a g-line exposure of a dyed resist [11]. The results encouraged Bol to study dyed resists for their own sake [12] and within a year most photoresist manufacturers had dyed resist products on the market.

Unfortunately, there is a general misunderstanding within the lithographic community about some of the basic properties of dyed photoresists. These

misunderstandings, fueled by the speed with which dyed resists have entered the market, have taken the form of myths about dyed resist performance. These myths include dramatic reductions in the standing wave effect, improved exposure latitude and improved linewidth control, among other claims. To sort out the fact from the fiction, a rigorous treatment of absorption will be applied to the exposure of dyed photoresists. Using this treatment, physical explanations of the observed behavior of dyed resists will be given. The effects of an absorbing dye on photoresist performance will then be modeled with the use of PROLITH (the Positive Resist Optical Lithography model) [19,20].

Absorption in Photoresists

Theory

The basic law of absorption is an empirical law with no known exceptions. It was first expressed by Lambert in differential form as

$$\frac{dI}{dz} = -\alpha I \quad (1)$$

where I is the intensity of light traveling in the z -direction through a medium, and α is the absorption coefficient of the medium and has units of inverse length. In an isotropic medium (i.e., α is not a function of z), eq. (1) may be integrated to yield

$$I(z) = I_0 e^{-\alpha z} \quad (2)$$

where z is the distance the light has traveled through the medium and I_0 is the intensity at $z=0$. If the medium is anisotropic, eq. (2) becomes

$$I(z) = I_0 e^{-A} \quad (3)$$

where $A = \int_0^z \alpha(z') dz' = \text{the Absorbance.}$

When working with electromagnetic radiation, it is often convenient to describe this radiation by its complex electric field vector. The electric field can implicitly account for absorption by using a complex index of refraction \mathbf{n} such that

$$\mathbf{n} = n - iK \quad (4)$$

The imaginary part of the index of refraction, sometimes called the extinction coefficient, is related to the absorption coefficient by

$$\alpha = 4\pi K/\lambda \quad (5)$$

In 1852 Beer showed that for dilute solutions of an absorbing material, the absorption coefficient of the solution is proportional to the concentration of the absorbing species in the solution:

$$\alpha_{\text{solution}} = ac \quad (6)$$

where a (molar absorption coefficient) = $\alpha \text{MW}/\rho$, MW is the molecular weight, ρ is the density and c is the concentration of the absorbing species. The stipulation that the solution be dilute expresses a fundamental limitation of Beer's Law. At high concentrations, where absorbing molecules are close together, the absorption of a photon by one molecule may affect the ability of another molecule to absorb light. Since this interaction is concentration dependent, it causes deviation from the linear relation (6). Also, an apparent deviation from Beer's law occurs if the index of refraction changes appreciably with concentration. For an N component homogeneous solid, the overall absorption coefficient becomes

$$\alpha_T = \sum_{j=1}^N \alpha_j c_j \quad (7)$$

We will now apply the concepts of macroscopic absorption to positive photoresist. A diazo-type photoresist (i.e., a typical positive resist) is made up of four components: a base resin R which gives the resist its structural properties, a photoactive compound M (also called a PAC), an exposure product P generated by the reaction of M with UV light, and a solvent S . Although photoresist prebaking is intended to drive off solvents, thermal studies have shown that a resist may contain 10-20% solvent after a typical prebake [21,22]. The absorption coefficient α is then

$$\alpha = \alpha_M M + \alpha_P P + \alpha_R R + \alpha_S S \quad (8)$$

If M_0 is the initial PAC concentration (i.e., with no UV exposure), the stoichiometry of the exposure reaction gives

$$P = M_0 - M \quad (9)$$

Eq. (8) may be rewritten as

$$\alpha = Am + B \quad (10)$$

where $A = (\alpha_M - \alpha_P)M_0$,

$B = \alpha_P M_0 + \alpha_R R + \alpha_S S$, and

$m = M/M_0$, the relative PAC concentration.

Both A and B are constants which do not change as the photoresist is being exposed. The relative PAC concentration goes from $m=1$ for unexposed resist to $m=0$ for completely exposed resist. Thus, α changes from a maximum of $A+B$ for unexposed resist to a minimum of B for completely exposed resist. This phenomenon is called resist bleaching. (Note that A can be negative, but for near-UV exposure of typical positive resists A is greater than zero.)

Suppose now a dye is added to the photoresist. Equation (8) can be modified to account for the added component:

$$a = a_M M + a_P P + a_R R + a_S S + a_D D \quad (11)$$

where a_D is the molar absorption coefficient of the dye and D is the dye concentration. Equation (10) does not change with the addition of the new component, but the constant B takes a new form:

$$B = a_P M_o + a_R R + a_S S + a_D D . \quad (12)$$

Thus, the effect of adding a dye to the photoresist is an increase in the value of B by the amount $a_D D$.

Experiment

To validate the above analysis, the effects of an added dye on the optical properties of photoresist were measured. First, known quantities of several dyes were added to a photoresist and the absorption parameters A and B were measured at various wavelengths. These same tests were performed on commercial dyed resists and some guesses were made as to the identity and quantity of the dyes used. The photoresist absorption parameters A and B and the exposure kinetics parameter C can be determined from a single experiment which measures the light transmitted through a photoresist film as it is being exposed (a detailed description of the experimental procedure is given elsewhere [23]). Using this technique, the parameter B can be measured for photoresists with varying amounts of added dye. UV spectrophotometry can also be used to measure B as a function of wavelength. This technique is useful in determining the wavelength of maximum absorption of a dye, λ_{max} .

For this study, the photoresists OFPR-800, with approximately 30.0% solids, and Hunt 204, with 27.8% solids content, were used. The dye Coumarin 314 [24] was added to the OFPR-800 in concentrations of 2 and 3% by weight based on the weight of solids in the photoresist. The Coumarin laser dyes are, in general, not very soluble in photoresist. Dye concentrations of 2-3% represent the maximum amount soluble for most of the Coumarin dyes tested. A second dye, Macrolex Yellow 6G [25], was added to the Hunt 204. This dye has a phenolic base and is quite soluble in Novolak based photoresists. Concentrations as high as 10% were mixed without difficulty. The resists were spin coated on quartz wafers to a thickness of about 1.0 μm . The samples were then convection oven prebaked at 95°C for 30 minutes or hot plate baked for 3 minutes at 90°C. The parameters A , B , and C were measured at the g, h, and i lines of the mercury spectrum. As expected, only the value of B changed with the addition of dye to the photoresist. The results are shown in Table I. From the measured values of B , the molar absorption coefficient of the dye, a_D , was determined. For convenience, units of $\mu\text{m}^{-1}/\%$ dye are used. These values (as a function of wavelength) are also listed in Table I. Note that these particular dyes are very effective in absorbing light at 436 nm (high a_D), are not very effective at 405 nm (low a_D), and are virtually transparent at 365 nm ($a_D \approx 0$). A UV spectrophotometer was used to measure $B(\lambda)$ for the different dye concentrations with the results shown in Figs. 1 and 2. It is interesting to note that both Coumarin 314 and Macrolex Yellow 6G have absorption maximums of 436 when dissolved in an appropriate solvent, but when in photoresist the peak absorbance shifts more than 20 nm toward the red. Finally, seven Coumarin dyes were added to samples of Hunt 204 in concentrations of 2% and the wavelength of maximum absorbance as well as values for B at several wavelengths were measured. This data is shown in Table II.

Obviously, dyes can be chosen which absorb in any number of different wavelength ranges. Other commercial dyes have also been investigated for their use in photoresist [26].

Also studied were commercially available dyed photoresists. Shown in Table III are the values of B for the undyed and dyed versions of four commercial resists. Note that three of the four commercial dyed resists contain extremely small amounts of added dye and all are designed for maximum absorption near the g-line of the mercury spectrum. By comparing the data in Tables I, II and III one can make some educated guesses as to the identities and quantities of the dyes used in the commercial resists. Though by no means a conclusive determination, the following are reasonable suggestions: Microposit 1400-27D1 and OFPR-800 AR-15 probably contain about 0.6% Coumarin 314, AZ 1318SFD contains about 1% Coumarin 6, and Ultramac PR914AR contains a high concentration of some dye which is probably not in the Coumarin family. As the use of Macrolex Yellow 6G has shown, there are probably many commercially available dyes which are more compatible with positive photoresists than are Coumarin dyes, and, as is the case with Macrolex, are much cheaper.

Standing Waves

When determining the effects of an absorbing dye on photoresist performance, the most obvious place to start is the standing wave effect. One of the first observations made when using a dyed photoresist is a reduction in the standing wave ridges of the resist profile near the top of the resist. Near the bottom the standing wave ridges appear to be unaffected by the dye. (One study suggested that adding dye to a photoresist can increase the size of the standing waves near the bottom of the resist [14].) The explanation often given for this observation seems quite simple: the dye absorbs light reflected from the substrate thereby reducing standing waves. This reduction occurs only near the top of the resist since near the bottom the reflected light has not been absorbed sufficiently to cause reduction in the standing wave intensity. Although this explanation may seem intuitively correct, it is quite false. To determine the true effects of absorption on the standing wave intensity a more rigorous approach will be taken.

An analytical expression for the standing wave intensity has been previously derived [1] and has the form

$$I \propto (e^{-\alpha z} + R e^{-2\alpha(d-z)}) - 2\sqrt{R} e^{-\alpha d} \cos(4\pi n(d-z)/\lambda) \quad (13)$$

where z is the depth into the resist, d is the resist thickness and R is the reflection coefficient of the resist-substrate interface. Note that there are two basic terms in this expression, a sinusoidally varying term with period $\lambda/2n$ and a much more slowly varying group of exponentials that can be thought of as a DC bias to the sinusoid. These two terms are referred to as the "interference effect" and the "bulk effect," respectively. The result is the typical standing wave intensity as shown in Fig. 3. Most of the important properties of the standing wave intensity can be obtained from equation (13). For example, the DC term decreases with depth into the resist due to absorption. The amplitude of the cosine term, however, reveals the information needed to determine the effects of absorption on standing waves. One can see immediately that this term, $2\sqrt{R} e^{-\alpha d}$, decreases as the absorption coefficient is made larger (for example by adding a dye to the resist). The same effect

can be obtained by increasing the resist thickness, d . Note, however, that the amplitude of the standing wave intensity is not dependent on z , the depth into the resist. Thus, the standing wave intensity is reduced by the addition of an absorbing dye, but is the same at the top of the resist as at the bottom. This effect can be seen in Fig. 3.

What, then, is the explanation for the observation described above, namely that the standing waves are reduced at the top of a dyed resist profile but not at the bottom? The reason is quite simple: the top of the resist is being overexposed relative to the bottom. As an example, consider a typical $1.0\ \mu\text{m}$ film of photoresist with 2.5% Coumarin 314 dye. G-line light passing through this film would have its intensity reduced by a factor of two upon reaching the bottom of the film. Thus, in order to give the bottom of the resist the proper exposure energy, exposure time would have to be doubled, thereby significantly overexposing the top of the resist.

To some it may not be obvious how overexposure can result in a reduction of the standing wave effect. To understand this phenomenon, one must understand one of the most important curves in photolithography, the exposure latitude curve. Shown in Fig. 4 is a graph of the linewidth of a critical dimension (CD) versus exposure energy. Note that the energy has been normalized to that which gives the nominal CD. One can view the standing wave intensity as a variation of the exposure energy about some average. If the bottom of the resist is properly exposed (energy = 1) and the standing wave intensity is ± 0.2 , the exposure latitude curve will predict the size of the standing wave ridges (i.e., the variation in linewidth), in this case about $0.2\ \mu\text{m}$ (Fig. 4). Since the bottom of the resist is exposed with energy 1, the top is exposed with relative energy 2. The same standing wave intensity for this overexposed case will result in a CD variation of only $0.08\ \mu\text{m}$. Thus, the standing wave ridges at the top of the resist are much smaller than those at the bottom even though the standing wave intensity is the same. The fundamental reason for this phenomenon is the greater exposure latitude of an overexposed photoresist feature.

Linewidth Control

Before determining the effects of dye additives on photoresist linewidth control, a review of the issues involved with linewidth control should be considered. For a given photolithographic system there are two primary variables which determine linewidth: focus and exposure (for proximity and contact printing the variables are exposure and mask-wafer separation). There are other variables, such as development and bake uniformities, which affect linewidth, but these are (or should be) second order effects. Focus errors, which take the form of autofocusing errors, wafer flatness, topography, etc., are not affected by resist absorbance and therefore will not be discussed further. Exposure errors include dose errors, illumination non-uniformities, changes in resist sensitivity and thickness, wafer reflectivity, etc., all of which affect the resulting linewidth. Thus, the ability to control linewidth variations depends on two factors: the shape of the exposure latitude curve and the ability to control exposure errors. To determine the effects of a dye additive on linewidth control, we will try to determine if the dye changes either the exposure latitude or the magnitude of exposure errors. Another issue, the effect of resist thickness changes, must be considered when investigating linewidth control on a non-planar substrate.

Exposure Latitude

There have been several studies which have claimed that adding dye to a photoresist can greatly improve exposure latitude. Unfortunately, this is another myth about dyed resists that has not been adequately demonstrated. For example, the work in references [14] and [15] claim that dyed resists improve exposure latitude. To prove this statement they show graphs of linewidth versus exposure in which the dyed resist has a "flatter" curve indicating improved latitude. In both cases, however, the exposure axis was not normalized to the nominal exposure energy, but rather the dyed and undyed resists were compared on the same absolute energy scale. Why can't exposure latitude curves be compared on absolute energy scales? Simply put, exposure errors tend not to be errors of a fixed amount, but rather errors as a percentage of the nominal (e.g., an illumination non-uniformity of $\pm 5\%$, a change in substrate reflectivity of 10%). Thus, exposure latitude data must be represented on a scale which reflects the type of exposure variations encountered in practice in order to be useful, i.e., a normalized energy scale. Because of the greater exposure energies required for dyed resists, an exposure latitude curve will appear "flatter" for a dyed resist than for the equivalent undyed resist on an absolute energy scale, even if the curves are the same on a normalized scale.

The above example is one way in which improper representation of linewidth data can lead to erroneous conclusions. The following is another example of how dyed resists can appear to have improved process latitude. If a nominally exposed 1 μm line in dyed photoresist has a linewidth of 1 μm at the bottom of the resist profile, the linewidth at the top of the resist will be much smaller. As was discussed previously, this is due to overexposure of the top of the resist with respect to the bottom. One could then measure the change in linewidth at the top of the resist with changing energy and plot ΔCD versus energy. Of course, the energy scale will be normalized to the nominal, in this case the energy which gives a 1 μm linewidth at the bottom of the resist. The result will be an apparent improvement in the exposure latitude over the undyed case. Again, however, this conclusion is false. The apparent latitude improvement is due only to the overexposure of the top of the resist feature. The error is a result of measuring linewidth at a location (the top of the resist) different from the location at which the determination of the nominal linewidth was made (the bottom of the resist).

An obvious question arises; how do the exposure latitudes of dyed and undyed resists compare when properly measured and presented? To answer this question, the simulation program PROLITH was used to predict the change in linewidth with exposure for resists with varying amounts of dye (i.e., different values of the resist absorption parameter B) on a non-reflecting substrate. Thus, only the effect of bulk absorption is considered. As can be seen from Fig. 5, the heavily dyed resist ($B = 2\mu\text{m}^{-1}$) shows somewhat of an improvement in exposure latitude over the undyed resist. The reason for this improvement is a complicated interaction of the effects of absorption and bleaching on the PAC concentration gradients along with the development properties of the resist [27]. The interference effect causes a variation in light intensity in the vertical direction. Nominally, exposure latitude depends on horizontal variations of light. Thus, one might expect exposure latitude to be independent of the standing wave effect. However, from a practical point of view, the standing waves cause a certain amount of uncontrolability in the shape of the resist sidewall which has the same effect as linewidth changes. Thus, the reduction of the standing wave intensity with dyed resist would have an advantageous effect on practical linewidth control. In summary, increased absorption does improve exposure latitude, but not to the degree previously reported.

Exposure Errors

The second aspect of linewidth control is the reduction of exposure errors. The presence of an absorbing dye can reduce exposure errors in some cases, e.g., reflections from the sidewall of an aluminum step. This is an example of a valid use for dyed photoresists - the reduction of reflective notching. Again, however, care must be taken in evaluating the results of experimental data. For example, a study which measures the change in the width of a resist line passing over a reflecting step for dyed and undyed resists will find that a heavily dyed resist shows much less linewidth change (measured at the top of the resist) than an undyed resist. However, a similar result will be obtained if the step is not reflective. Once again, the overexposure of the top of the resist line causes an apparent improvement in linewidth control. Thus, it is very difficult to evaluate from experimental data the ability of a dyed resist to reduce exposure errors.

Resist Thickness Latitude

Changes in resist thickness cause changes in linewidth for a constant exposure energy. Both the bulk effect and the interference effect play a role in resist thickness latitude. Figure 6 shows the exposure energy required to produce the nominal linewidth for a one micron feature with changing resist thickness for glass, silicon and aluminum substrates (simulated with PROLITH). One can clearly see that the interference effect can cause great changes in linewidth for only slight changes in resist thickness. Since one effect of dye additives is to reduce the interference effect, dyed resists show improvement in resist thickness latitude on reflecting substrates (Figure 7). This can be a great advantage when imaging over topography and in other situations where resist thickness varies.

Drawbacks of Dyed Resists

The negative aspects of dyed photoresists are well known: increased exposure time and sloped resist sidewalls. Using PROLITH these factors can be quantified as a function of the unbleachable resist absorption parameter, B. Shown in Fig. 8 is the relative increase in exposure energy required to produce a nominal 1 μm linewidth at the bottom of the resist feature as the value of B is increased. Fig. 9 shows the reduction in the resist sidewall angle as resist absorption is increased. A reduction of the sidewall angle can greatly reduce the linewidth control during subsequent etching operations. Obviously, the advantages of reduced exposure error and greater resist thickness latitude must be carefully weighed against the disadvantages of dyed resists as outlined herein.

Development

The above analysis is based on the effects of an absorbing dye on the exposure of a positive photoresist. For the purposes of modeling, the development parameters were assumed to be constant and unaffected by the presence of the dye. Previous studies, however, indicate that dyes do affect the development process [13,14]. In fact, the addition of 1.28% Coumarin 314 to a Shipley 1400 resist was found to significantly reduce the development rate, possibly dominating the performance aspects of the

dyed resist [13]. As was shown in a previous section, three of the four commercial dyed resists tested have extremely small quantities of added dye. The modeling studies presented here have shown that values of B in this range ($\sim 0.2 \mu\text{m}^{-1}$) do not have much effect on exposure latitude or exposure errors. Thus, many of the observed effects (e.g., ref. [17]) for these commercial dyed resists may be due mainly to developmental effects. Clearly, experimental determination of the effects of various dyes on the development process is essential in understanding and modeling the performance of dyed photoresists.

Conclusions

Over the past three years many claims have been made concerning the performance of dyed photoresists. As has been shown, some of these claims are myths. The reasons for the acceptance of these myths are many: non-rigorous or intuitive explanations of the effects of absorption, misrepresentation and misinterpretation of experimental data, and most of all, the lack of an appropriate amount of skepticism about the claims. Interestingly enough, this problem points out an important application of process modeling. The simulations given in this paper, which show quite clearly the true behavior of dyed photoresists, could easily have been performed three years ago during the first stages of research into this subject. In fact, it was the use of lithography modeling which first suggested the possibilities of dyed resists [10]. Process modeling represents an almost essential tool which, when properly applied, can aid considerably in the understanding of the complex process of optical lithography.

In summary, the following points can be made:

- 1) Dye additives reduce the standing wave intensity. This results in a reduced standing wave effect and improved resist thickness latitude.
- 2) Many *observed* reductions in the standing wave effect are not due so much to reductions in the standing wave intensity, but to overexposure as a result of bulk absorption.
- 3) Dye additives have a small effect on exposure latitude. Apparent improvements in exposure latitude are due to overexposure and/or standing wave reduction.
- 4) Dye additives can reduce some exposure errors such as reflections from metal steps and scattering from rough surfaces [28].
- 5) The decrease in etch process latitude due to reduced sidewall angle may outweigh the improvements in resist linewidth control resulting in a *net reduction* of linewidth control. This factor is very process dependent and must be evaluated for each pattern transfer process.
- 6) Development effects, which have yet to be characterized, play a significant role in determining the performance of dyed resists.
- 7) The commercial dyed resists tested (Ultramac PR914AR excepted) contain small amounts of added dye, such that the optical effects of the dye are small, though not completely negligible.

A final conclusion cannot be made in general about the appropriateness of using dyed photoresists. The analysis given in this paper, however, should convince the lithography engineer that careful consideration must be given to the disadvantages as well as the advantages of dyed photoresists and that extreme care must be taken when evaluating linewidth data for dyed resists.

Acknowledgments

The author wishes to thank John Covington of Texas Instruments for supplying samples of the dyed OFPR photoresist, and Ted Grauch and Aaron Radomski for helping to measure the optical parameters of the dyed resists.

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Figure 1: Absorption parameter $B(\lambda)$ for OFPR-800 with various amounts of added Coumarin 314 dye.

Figure 2: Absorption parameter $B(\lambda)$ for Hunt 204 with various amounts of added Macrolex Yellow 6G dye.

Figure 3: Standing wave intensity for dyed and undyed photoresist on silicon.

Figure 4: Typical photoresist exposure latitude curve showing how overexposure reduces the standing wave effect.

Figure 5: Exposure latitude, as predicted by PROLITH, for undyed and heavily dyed resist on a non-reflecting substrate.

Figure 6: Variation in exposure energy required to produce the nominal linewidth as resist thickness is changed for glass, silicon and aluminum substrates (PROLITH simulations).

Figure 7: Variation in linewidth as resist thickness is changed for resist with varying dye concentration (silicon substrate, PROLITH simulations).

Figure 8: Relative increase in exposure energy, as predicted by PROLITH, required to image a $1\ \mu\text{m}$ space as the dye concentration is increased.

Figure 9: Decrease in sidewall angle as the dye concentration is increased, as predicted by PROLITH.

Table I
Measured optical absorption parameter B for
various dye concentrations

	365 nm	405 nm	436 nm	λ_{MAX} (nm)
OFPR-800 & Coumarin 314:				
B (μm^{-1}) no dye	0.30	0.10	0.09	
B (μm^{-1}) 2% dye	0.30	0.23	0.67	455
B (μm^{-1}) 3% dye	0.30	0.30	0.90	455
a_D ($\mu\text{m}^{-1}/\%$ dye)	0.0	0.07	0.28	
Hunt 204 & Macrolex 6G:				
B (μm^{-1}) no dye	0.21	0.05	0.04	
B (μm^{-1}) 1% dye	0.21	0.11	0.24	459
B (μm^{-1}) 5% dye	0.25	0.28	0.99	459
B (μm^{-1}) 10% dye	0.28	0.65	2.22	459
a_D ($\mu\text{m}^{-1}/\%$ dye)	0.006	0.06	0.21	

Table II
 Optical properties of Hunt 204 with various added dyes
 (2% by weight of solids)

	B(365 nm) (μm^{-1})	B(405 nm) (μm^{-1})	B(436 nm) (μm^{-1})	λ_{MAX} in photoresist (nm)	λ_{MAX} in ethanol (nm) [†]
No Dye	0.216	0.053	0.036	-	-
Coumarin 1	0.524	0.424	0.072	394	373
Coumarin 2	0.619	0.208	0.045	370	366
Coumarin 4	0.233	0.069	0.052	325	372
Coumarin 6‡	0.234	0.095	0.217	476	458
Coumarin 152	0.338	0.369	0.319	425	397
Coumarin 311	0.613	0.399	0.049	384	367
Coumarin 314	0.224	0.201	0.573	455	436

[†] Taken from product literature [24]

[‡] Maximum solubility was less than 2%

Table III
Optical properties of commercial dyed photoresists

	B(365 nm) (μm^{-1})	B(405 nm) (μm^{-1})	B(436 nm) (μm^{-1})	λ_{MAX} (nm)
Ultramac PR914	0.23	0.06	0.07	-
Ultramac PR914AR	0.63	0.78	1.11	443
Microposit 1400-27	0.27	0.06	0.07	-
Microposit 1400-27D1	0.36	0.15	0.25	455
OFPR-800	0.28	0.11	0.07	-
OFPR-800AR	0.38	0.22	0.24	459
AZ 1350J	0.28	0.05	0.04	-
AZ 1318SFD	0.31	0.12	0.20	481

Absorption Parameter (μm^{-1})

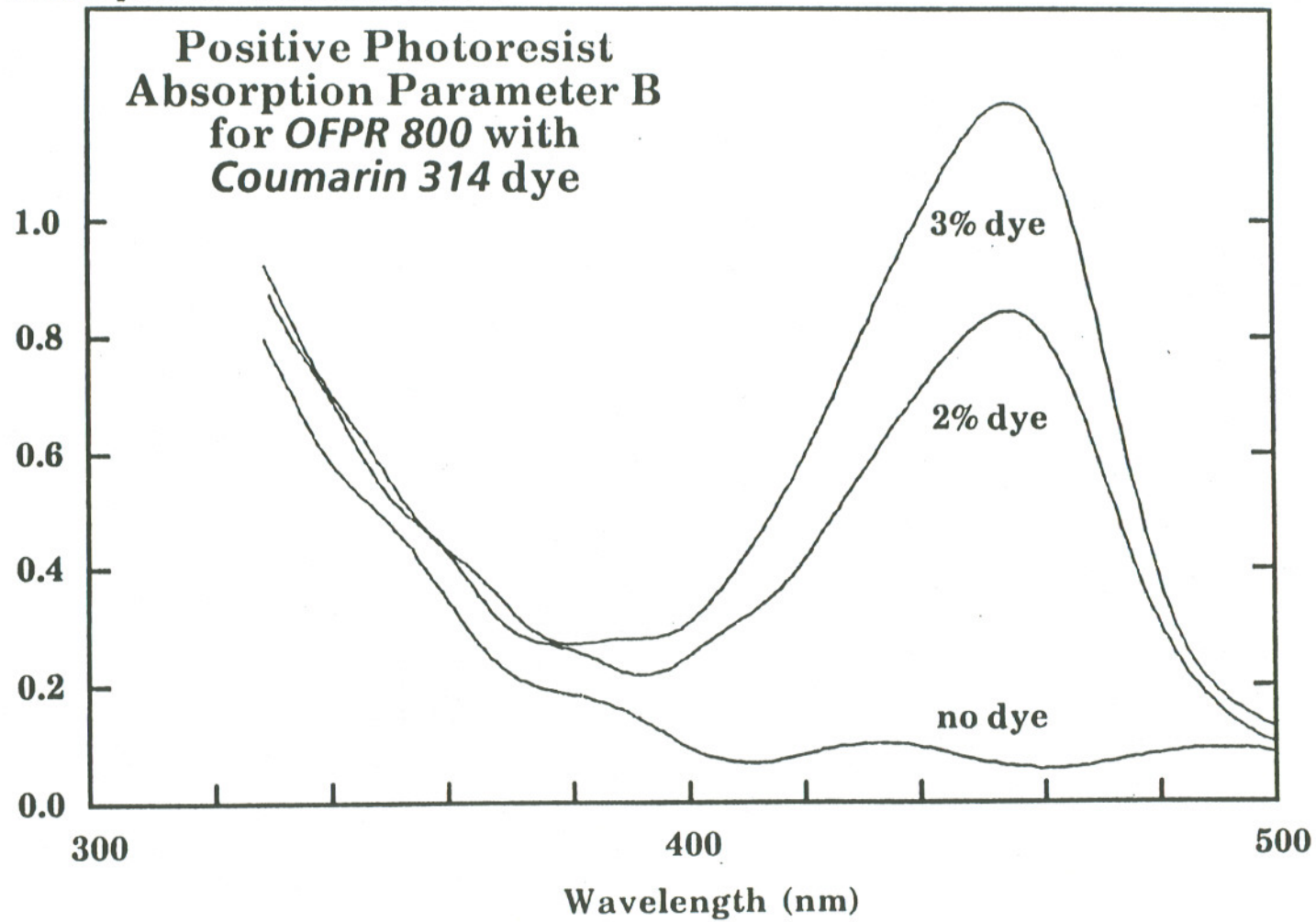


Figure 1

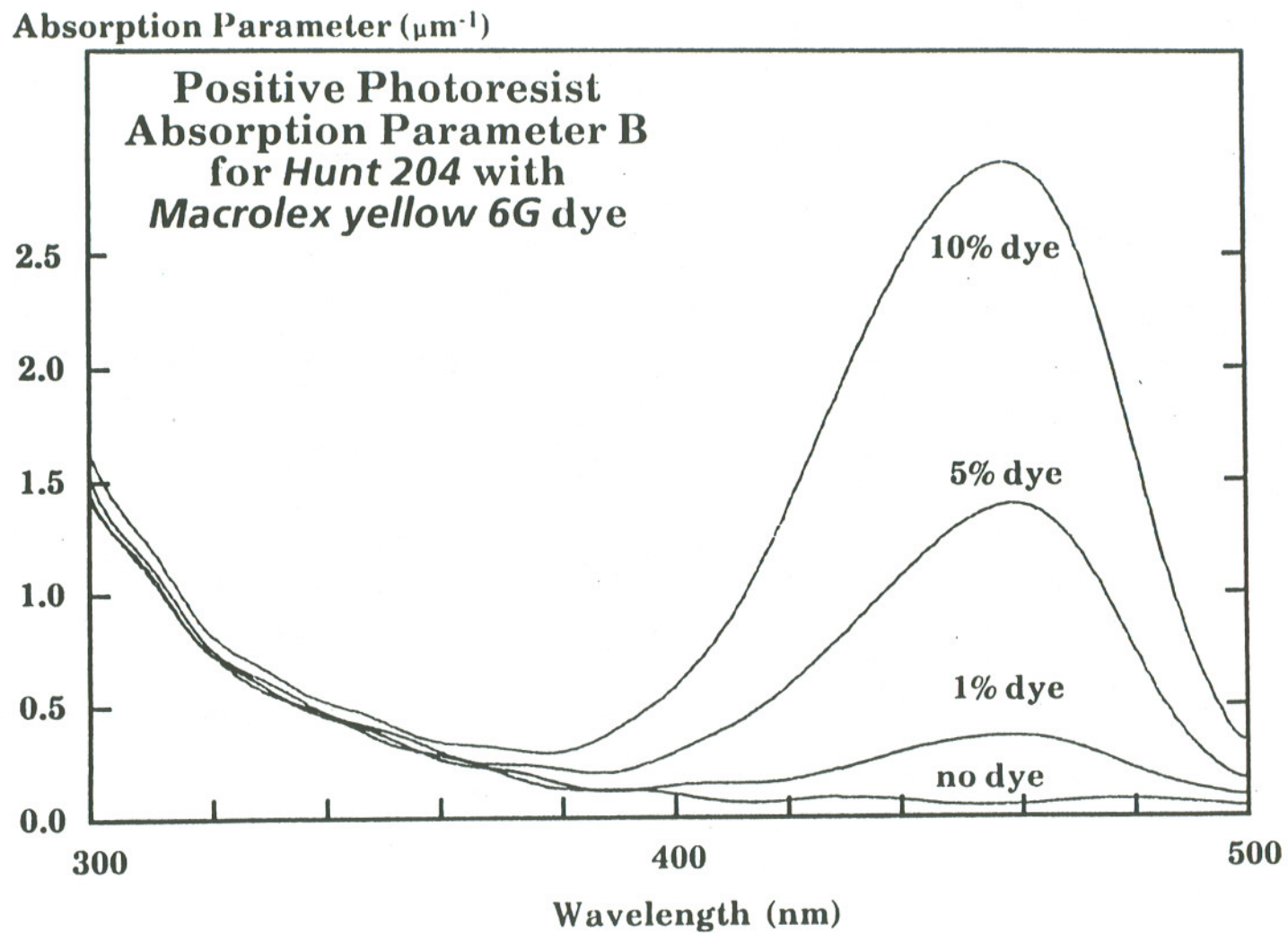


Figure 2

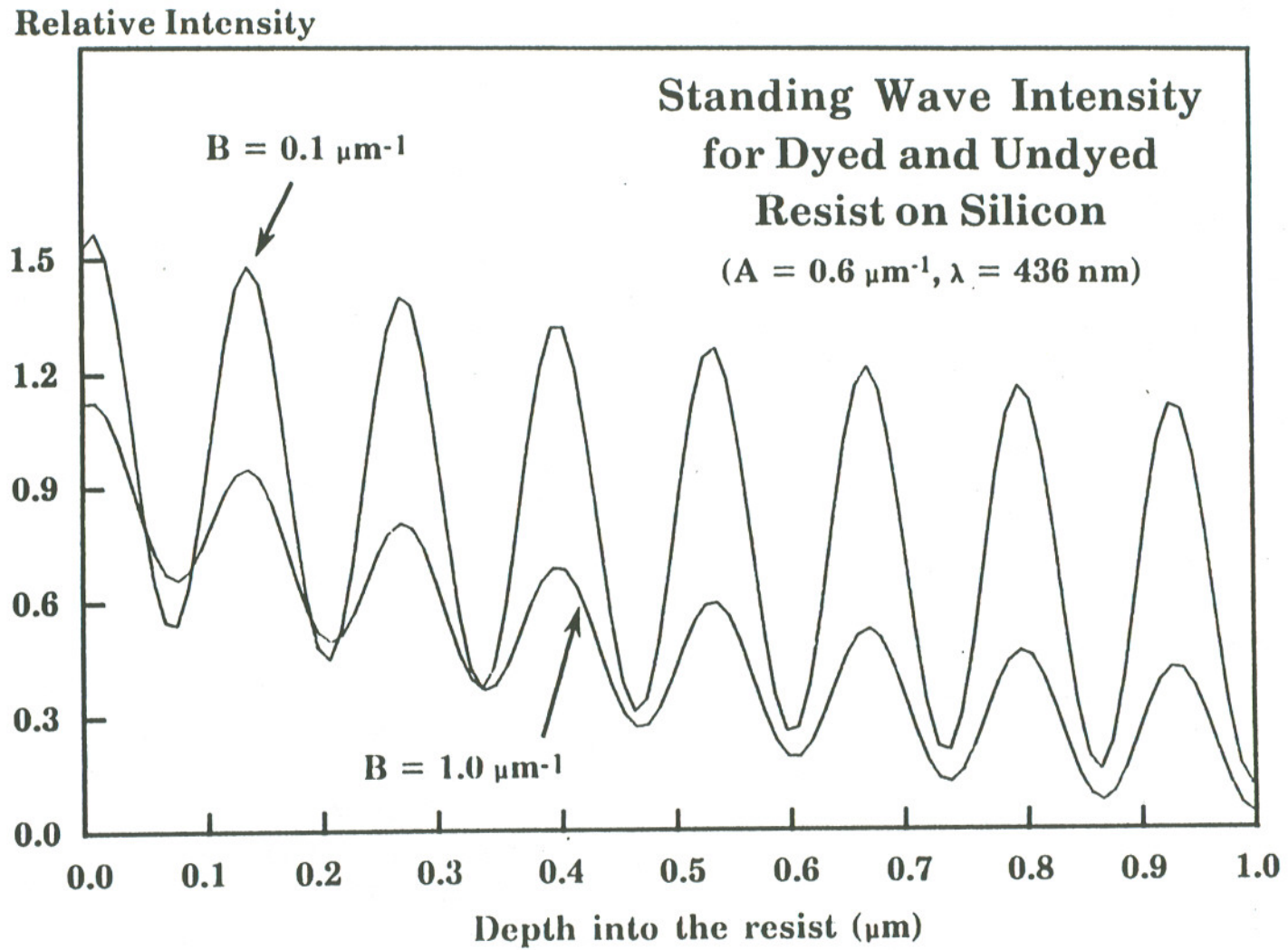


Figure 3

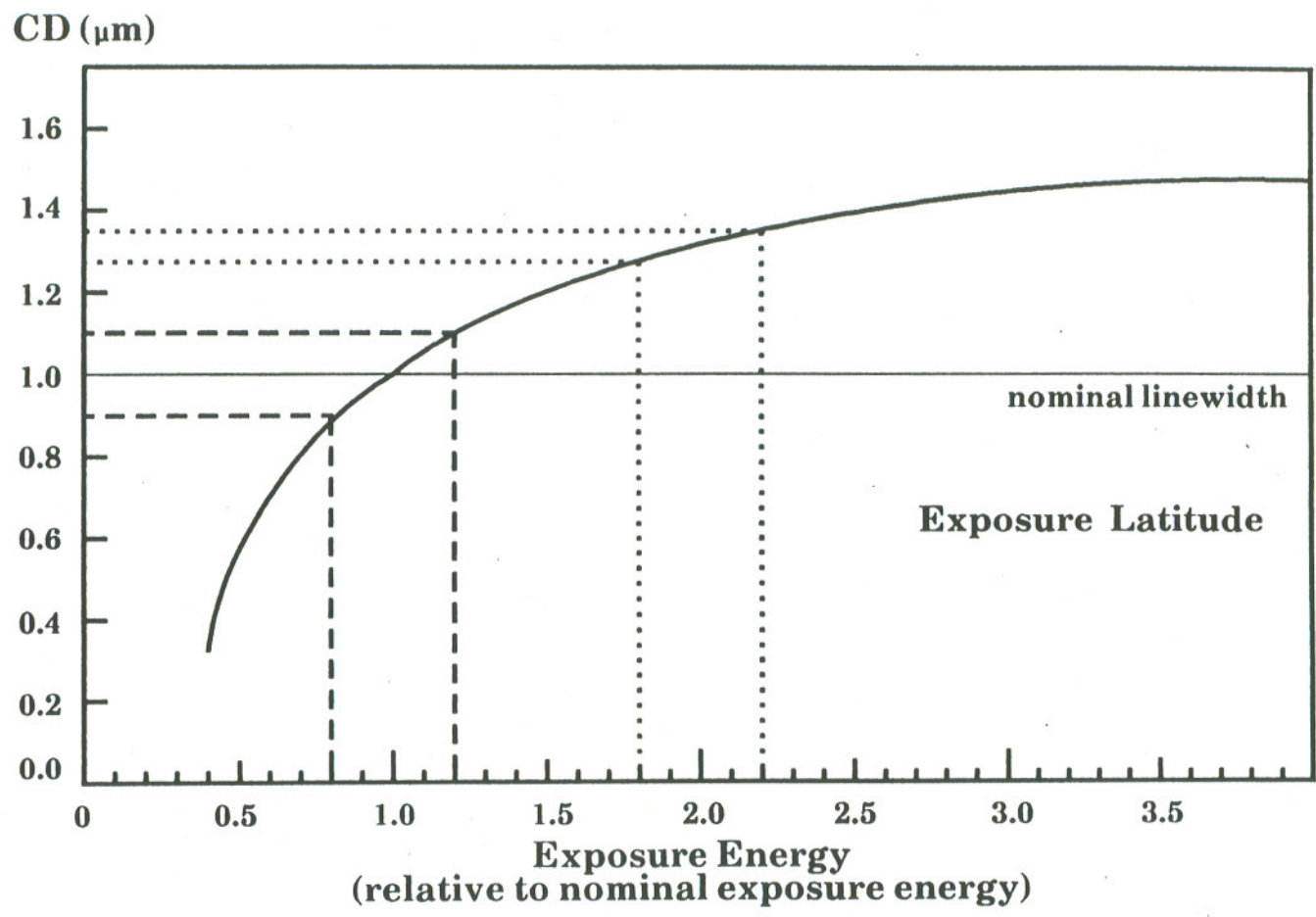


Figure 4

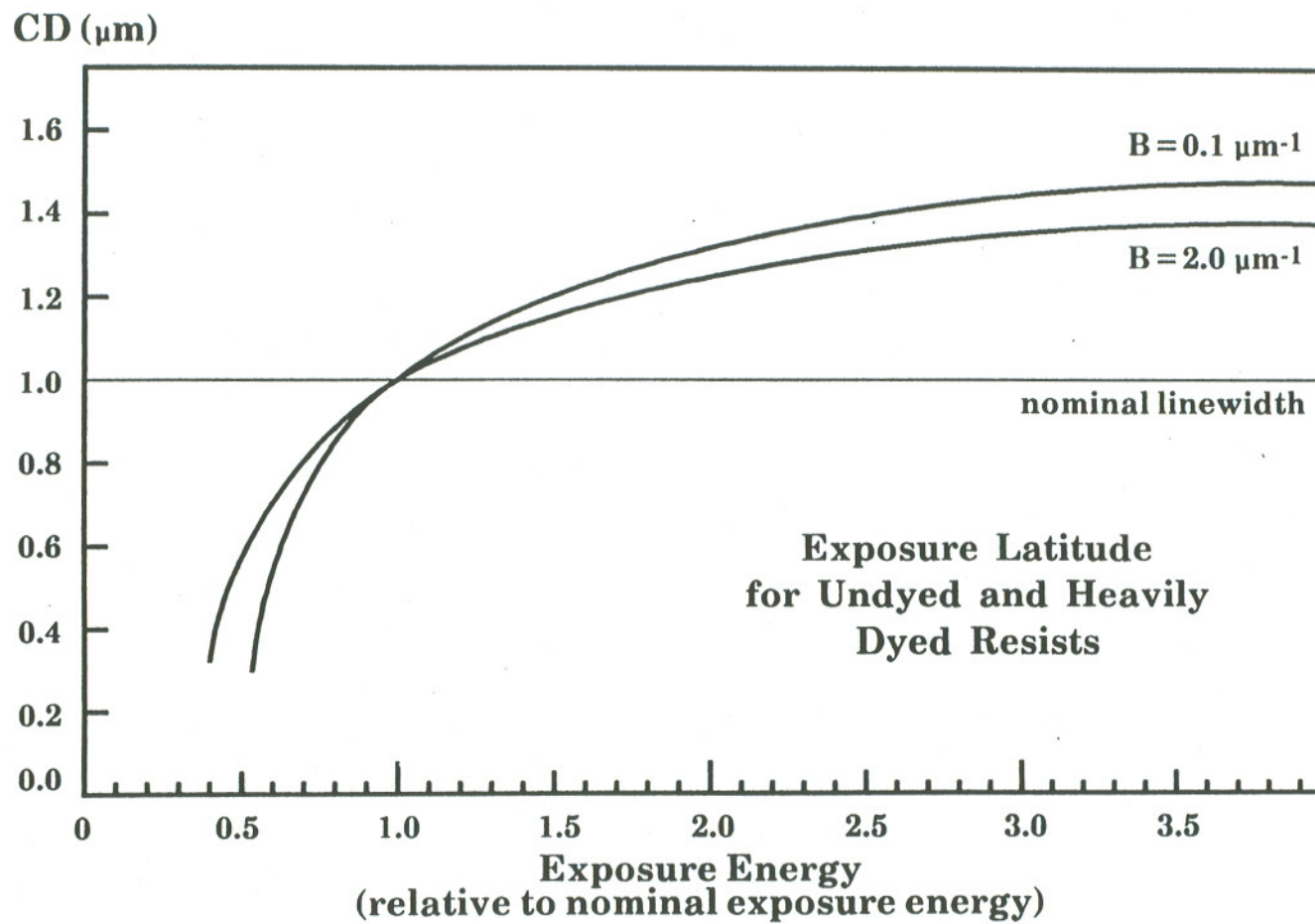


Figure 5

Resist Thickness Latitude

Exposure Energy (mJ/cm²)

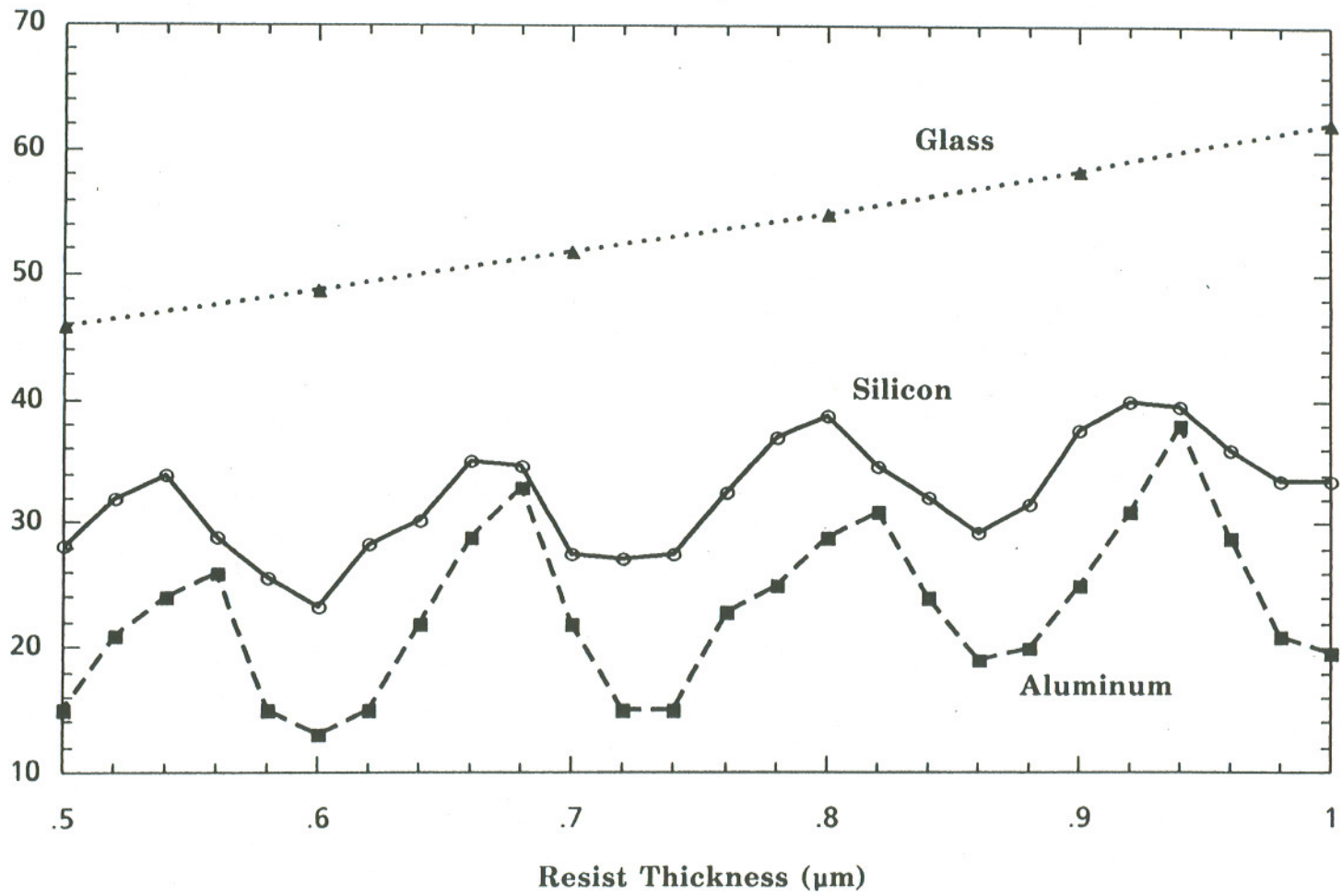


Figure 6

Linewidth Variations with Resist Thickness

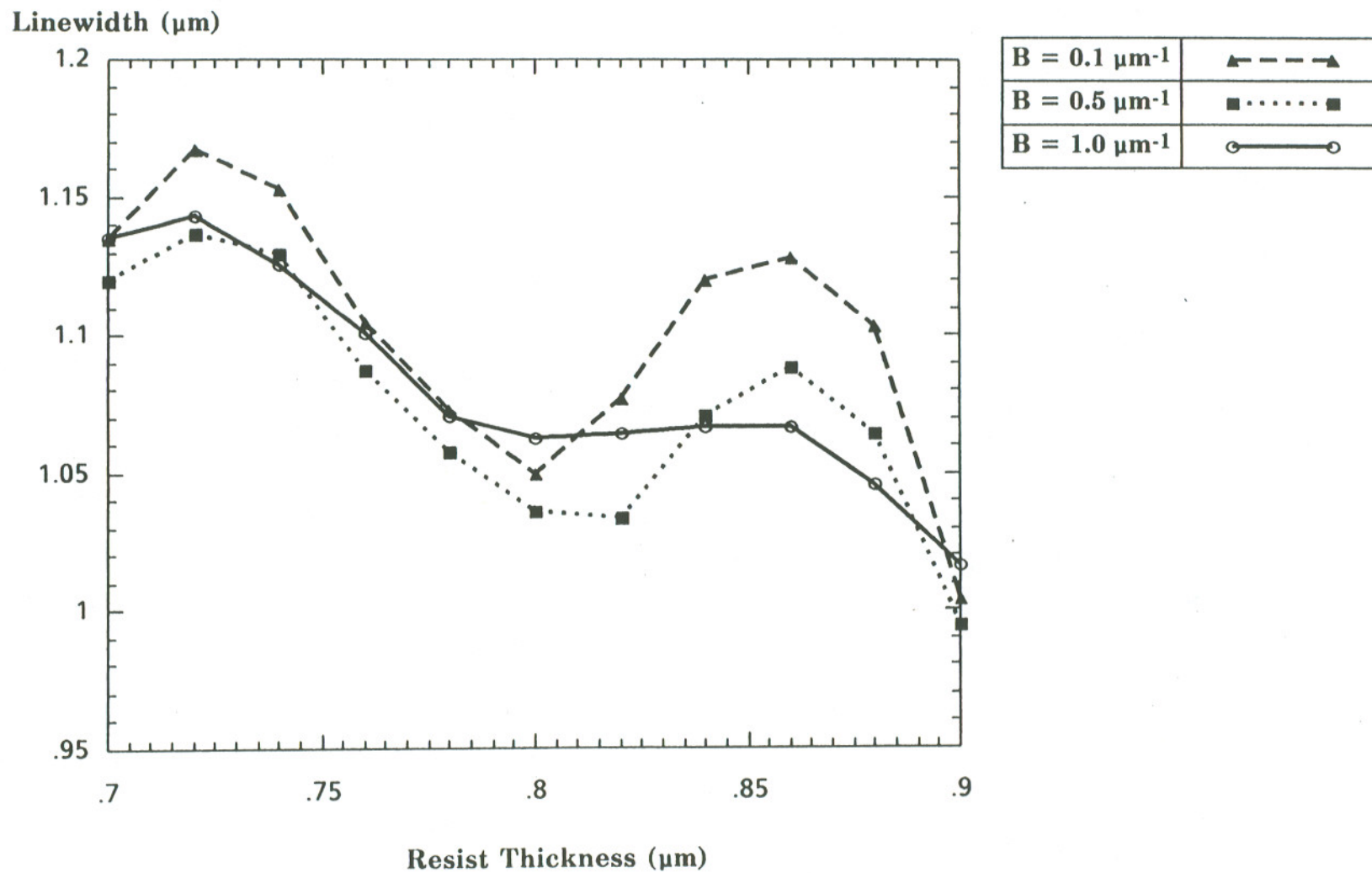


Figure 7

Exposure Penalty for Dyed Resists

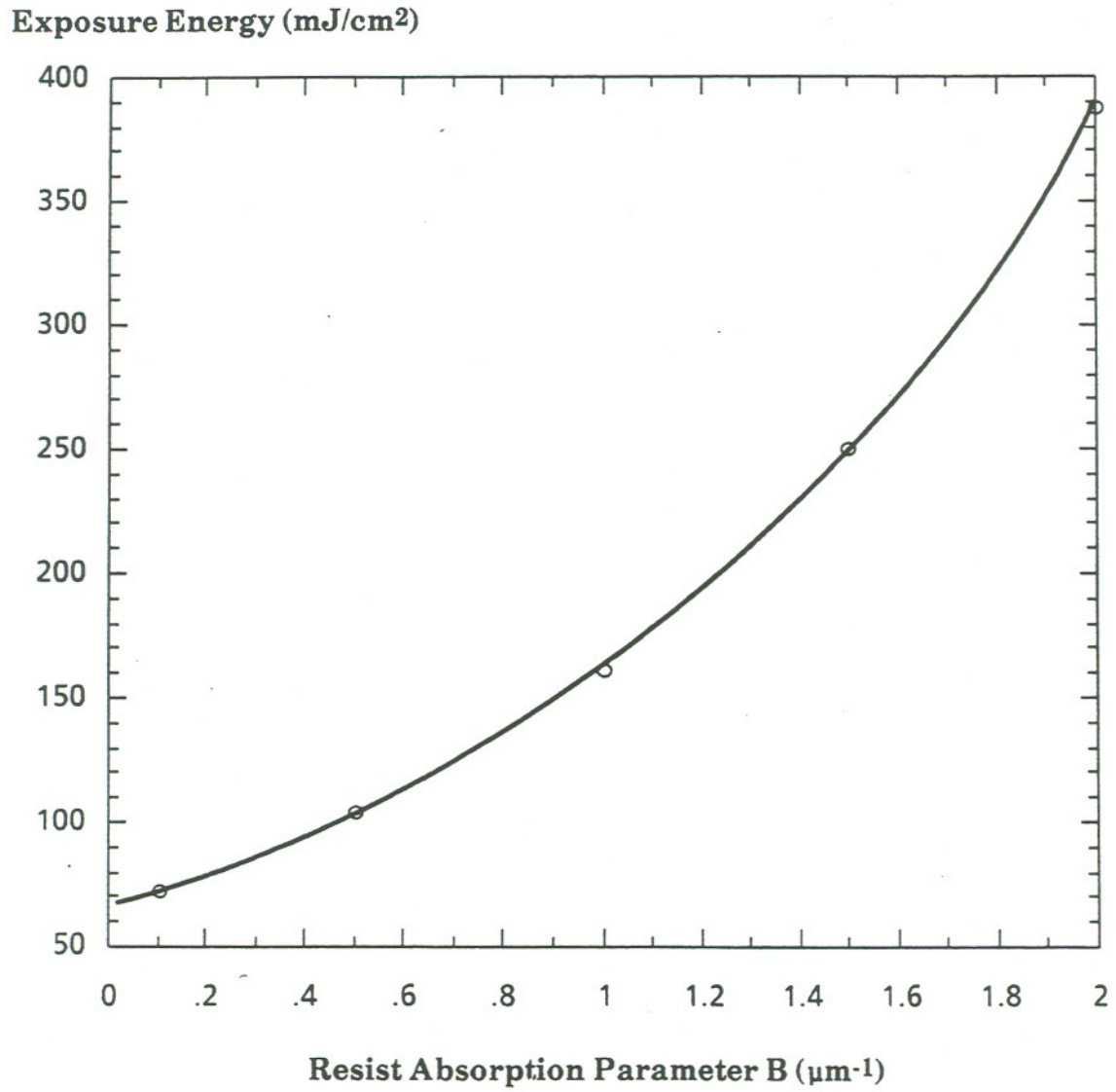


Figure 8

Sidewall Angle Reduction for Dyed Resists

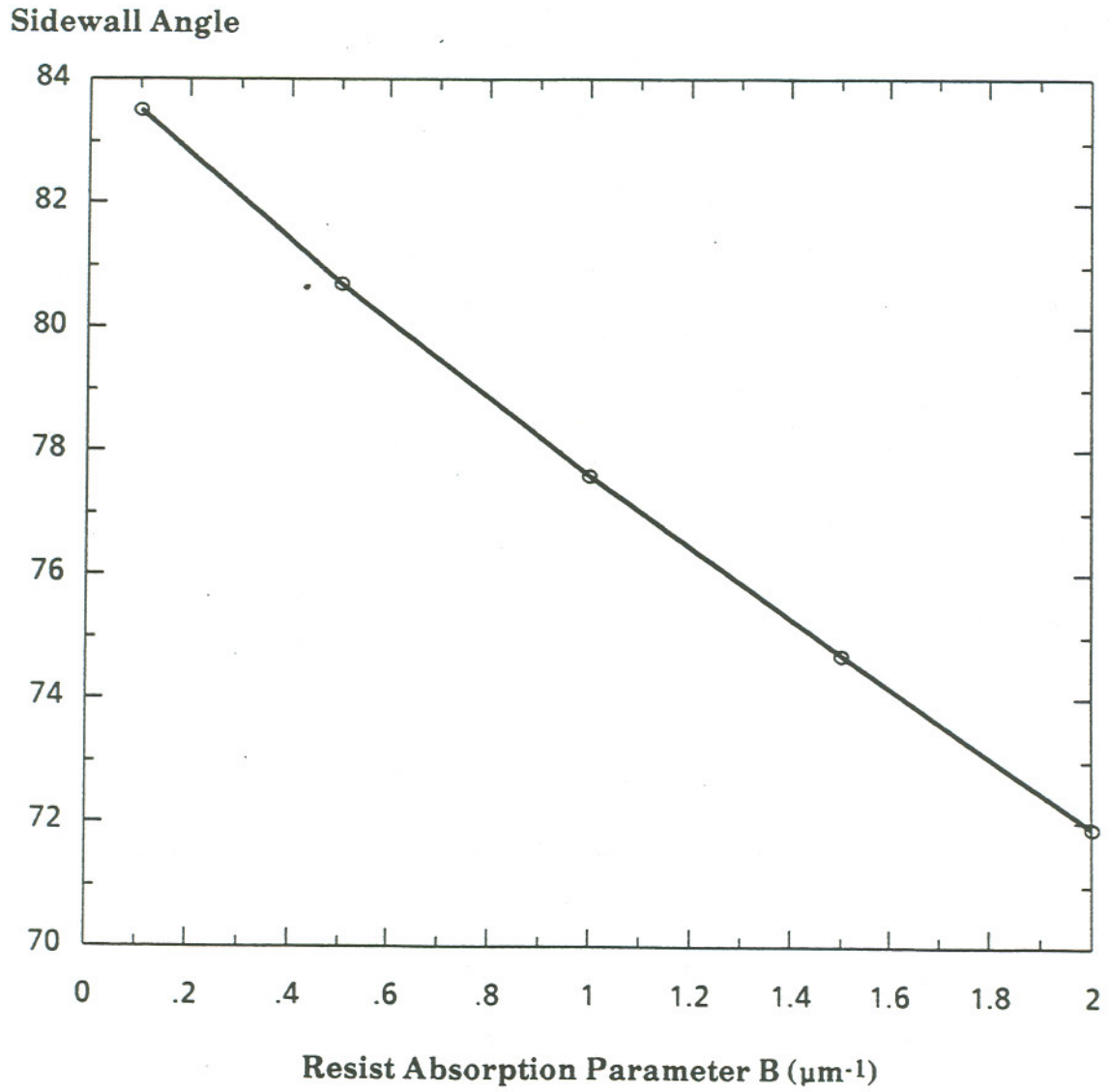


Figure 9