STUDIES OF OPTICAL LITHOGRAPHIC PROCESS WITH THE AID OF PROLITH/2

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ABSTRACT

PROLITH/2, a tool for modelling and analyzing photolithographic processes, was used to explore two statistically designed experiments. The first was the aerial image formation and the second was resist development process. Results are presented to illustrate the software capability.

INTRODUCTION

PROLITH/2 (Positive Resist Optical Lithography Model) is user friendly software developed to simulate standard and advanced lithographic processes used in the fabrication of integrated circuits. In particular, it can simulate (1) the formation of an aerial image of a single mask feature by a projection optical system, (2) exposure of a light sensitive photoresist by this image, and (3) development of the exposed photoresist to produce a relief image [1].

One option in PROLITH/2 is to operate in the "Single Run" mode. In this mode, a simulation of the exposure and development of a single mask feature is done. The results are shown in Figure 1. The first graph is the aerial image at the top of the photoresist. The second graph is the standing wave intensity in the resist. The third graph shows the relative concentration of photoactive compound (PAC), and the final graph is the photoresist profile [1].

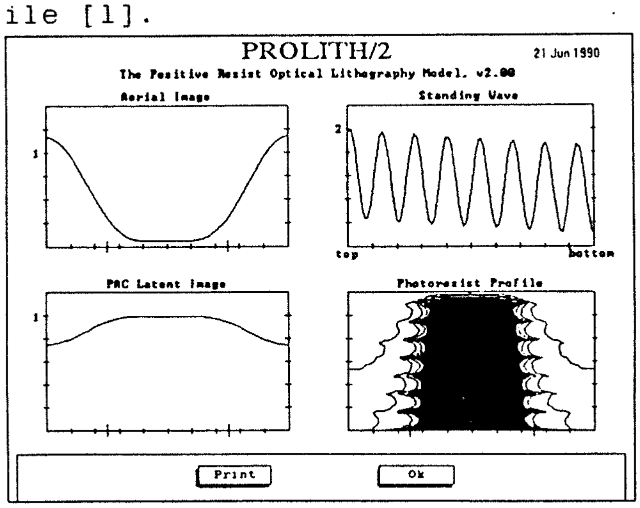

Figure 1: Single Run Graphical Output [1].

"Multiple Run" mode is the second option of PROLITH/2. In this mode, one of the input parameters shown in Figure 2 is selected with a desired range to study its effects on one of the eight outputs. These eight outputs are: Image Log-Slope, PAC Gradient, Film Stack Reflectivity, Resist Linewidth, Sidewall Angle, Aerial Image, Resist Gamma, and Clearing Dose [1].

1. Wavelength
2. Numerical Aperture
3. Partial Coherence
4. Width
5. Pitch
6. Mask Bias
7. Focal Distance
8. Fixed Defocus
9. Flare

11. Resist Thickness
12. Resist A
13. Resist B
14. Resist C
15. Prebake Temperature
16. Prebake Time

21-29. Thickness of Layers 1-9

31. CEL Thickness
32. CEL A
33. CEL B
34. CEL C

41. Exposure Energy

51. PEB Diffusion Length
52. PEB Temperature
53. PEB Time

61. Development Time
62. Rmax
63. Rmin
64. Threshold m
65. Selectivity n
66. Relative Surface Rate
67. Inhibition Depth

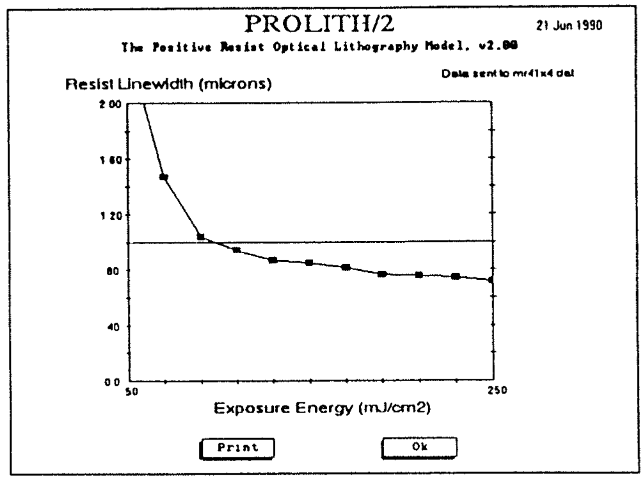

Figure 2: "Multiple Run" Input Variables and Multiple Run Graphic output [1].

"Focus-Exposure Matrix" is the third option of PROLITH/2. It is a plot of resist linewidth as a function of focus for different values of exposure with all other parameters fixed. The output for this run mode is shown in Figure 3 [1].

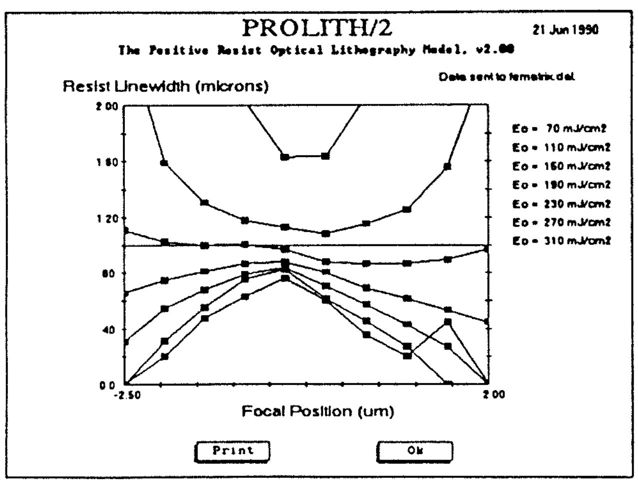

Figure 3: Focus-Exposure Run Graphical Output [1].

In this project, two photolithographic process, the formation of aerial image and development, were characterized using PROLITH/2 by studying the effects of exposure tools properties and variations in process parameters on resulting resist profiles. RS/Discover, a statistical analysis software package, is used to analyze the results.

EXPERIMENT

Box-Behnken designed experiments were generated to study the parameters that would affect the aerial image formation and resist development process. For each process, response(s), which could measure the process performance, and parameters, that could affect this response(s), were determined. Then, they were input into RS/Discover for the generation of an experiment design. A Worksheet which contained the required number of experimental runs and conditions was created. Simulations were then carried out in PROLITH/2 according to the worksheet to get the necessary results. The results were input into RS/Discover to study the effects of each parameter.

For the process of aerial image formation, the response was the aerial image contrast. This is the slope of the natural log of the aerial image at the nominal mask edge. The parameters which would affect this response were the objective NA, coherence, nominal linewidth, defocus, and the relative background intensity. The minimum resolution of a lens are found by

$$R = K \times \text{lamda} / NA \qquad (1)$$

where K is a constant which depends on the optical tool and lamda is the wavelength. From this equation, it is found that resolution can be improved by shortening wavelength and increasing NA with the expense of lowering the depth of field, DF [2]. Its relation with NA and wavelength is

$$DF = +/- \text{lamda} / (2 \times NA^{**}2) \qquad (2)$$

Coherency or the coherence factor, σ, is defined as

$$\sigma = \frac{\text{Numerical aperture of condenser}}{\text{Numerical aperture of objective}} \qquad (3)$$

For a coherent source, the main drawback is the severe image degradation due to diffraction. However, an incoherent source lowers the contrast of the optical system, the effective resolution, and the depth of focus of a projected image [2]. In this experiment, the wavelength was limited to 436nm and the image was assumed in perfect focus. The range used for the NA when generating the experiment design in RS/Discover was from 0.3 to 0.6, the range for coherence was 0.3 to 0.9, the linewidth was from 0.4um to 1.0um, the defocus was from 0.0um to 2.0um, and the flare was from 0.0 to 0.1.

For the development process which formed a relief image in photoresist, the responses were critical dimension, and sidewall angle. The parameters which could affect these two responses were pre-bake temperature, exposure energy, post exposure bake temperature, and development time. Resist prebake is to remove the solvent carrier from the other image-formation ingredients or

solids. Too low or too high prebake temperature would vary the amount of solvent left, which may interfere with the radiation chemistry. Different exposure-development combinations would then be required to obtain the same linewidth [2]. Exposure energy causes the photoresist chemical reaction. It can determine the amount of crosslinking in negative resist or scissoning in positive resists. Different degrees of crosslinking or scissoning would result in different critical dimensions. Post exposure bake is used to remove standing waves or amplify resist images [2] and development time controls the developed resist linewidth. Since the pre-bake time and temperature, and the post exposure bake time and temperature are directly related, only the temperatures were chosen to vary. The pre-bake time and the post exposure bake time were fixed at 30 minutes in a conventional oven. Other fixed settings for this experiment were the resist thickness of 1um; the mask pattern of 1.2um equal lines and spaces; a wavelength of 436nm; NA of 2.8, coherence of 0.3; focal distance of 0um (perfect focus); defocus of 0.5um; and background intensity of 0.02mj/cm**2.

The resist that was chosen to be studied was System 8 from Shipley. The reasons for choosing these values and resist were to simulate a stepper at RIT, which has a NA of 0.28. To obtain a decent aerial image with this NA, the above values of coherence, defocus, and flare were needed and the resist is one of the new resists at RIT. For the pre-bake temperature, the range used in the experiment was from 80 C to 120 C. The exposure energy was from 170mj/cm**2 to 200mj/cm**2, the post exposure bake was from 80 C to 110 C, and development time was from 80 sec to 100 sec.

EFFECTS ON THE FORMATION OF AERIAL IMAGE

Through the simulations, it was found that larger NA, smaller coherence, less defocus, and little flare could improve the quality of an aerial image. For a useful image, the image log slope should at least equal to 4. A model with twenty one terms were generated. However, not all of these twenty one terms of the model were signigicant. For the five process variables, NA, coherence, nominal linewidth, defocus, and background intensity, used, all five of them had significant linear effects on the process. Figure 4 show how each parameter affects the image log slope. The small boxes show the simulation results and the lines are the adjusted aerial image log slope. For coherence, defocus, and flare, the effects on the aerial image log slope were linear. For NA and nominal linewidth, the effects, however, were also quadratic.

The relations between any two combinations of parameters were also studied with RS/Discover. When NA was small, it was directly related to coherence, defocus, and flare. However, they became inversely related as NA increased. Linewidth, according to equation 1, should have a linear inverse relation with NA. However, it was found that as linewidth got wider, the relation became more quadratic. This was because as linewidth increased,

resolution was no longer a limiting factor. Therefore, NA would have less effect on the minimum linewidth resolution. The relations between NA and coherence, linewidth, and flare, but not defocus, were very linear when NA was small. According to Equation 2, the relation between NA and defocus was quadratic. Again, when NA increased, it began to loss its effects, and the relation became more linear.

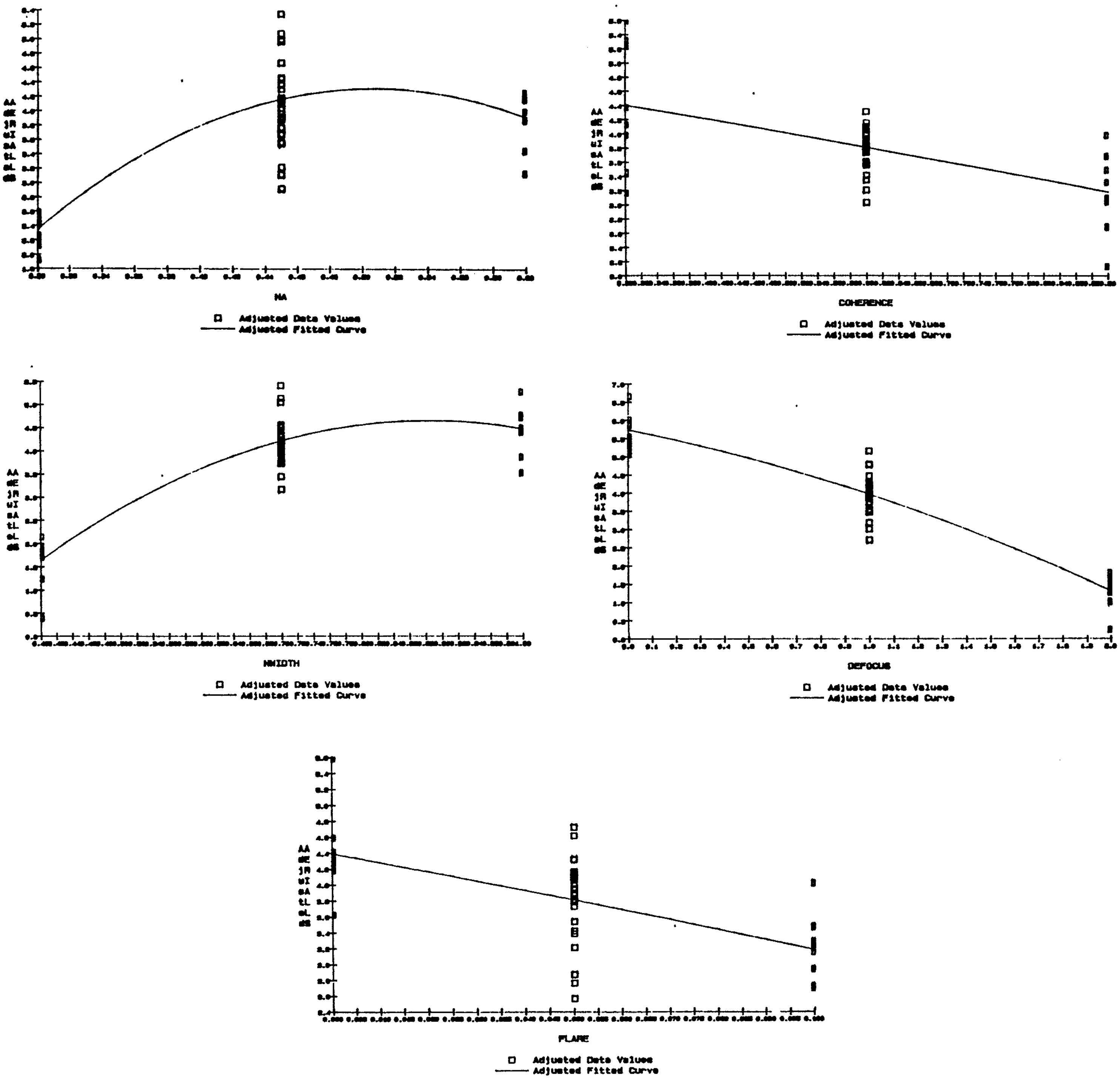

Figure 4: Effects of NA, Coherence, Linewidth, Defocus and Flare on Aerial Image.

Simulation results show that with an aerial image log slope of 4 or above, as coherence increased, the nominal linewidth that could be resolved also got wider. Defocus, however, decreased when coherence increased. As stated earlier, when an illumination source changed from coherent to incoherent, the contrast of the system, the effective resolution, and the depth of focus of a projected image would be lowered [2]. Coherence and flare were indirectly proportioned to each other. To get a good aerial image, small coherence factor and little flare are desired. Linewidth and defocus were directly related to each other, and it could be shown by combining Equation 2 and 3 together. For defocus and flare, they both started out with a linear relation with linewidth, but got more quadratic as linewidth continued to increased. The way that defocus and flare are related was inverse but linear. As defocus increased, flare has less effects on aerial image than when defocus was small.

Besides linear and quadratic effects, there were also some interaction effects between parameters. However, only the interaction effects of NA and defocus, coherence and linewidth, and coherence and defocus were significant.

EFFECTS ON THE DEVELOPMENT PROCESS

The simulation results of critical dimension and sidewall angle were input into the computer designed experiment in RS/Discover. Figure 5 show how each parameter affects the critical dimension, and Figure 6 show their effects on sidewall angle. Increases in exposure energy, prebake temperature, and development time could reduce the critical dimension of the resist. Post exposure bake, however, would increase the linewidth when a higher temperature was used. Exposure energy and development time affect the resist linewidth linearly, while prebake temperature and post exposure bake temperature's effects were quadratic. For sidewall angle, the effects of each parameter were almost just the opposite of their effects on critical dimension. Exposure energy and development time still have linear effects, and prebake and post exposure bake temperature have a quadratic effects. However, increases in exposure energy, prebake temperature, and development time now increased the sidewall angle, while post exposure bake temperature would decrease it.

The relation between any two combinations of the parameters were studied. Exposure energy and development time, as shown earlier, have the same effects on critical dimension and sidewall angle. Their relation with prebake temperature were also very similar. Within the operation range, a quadratic relation was seen between prebake temperature and exposure energy, post exposure bake temperature, and development time, when the temperature was low; while they became more linear when temperature increased. In order to duplicate the same image, a lower exposure energy or shorter development time could compensate for a higher prebake temperature.

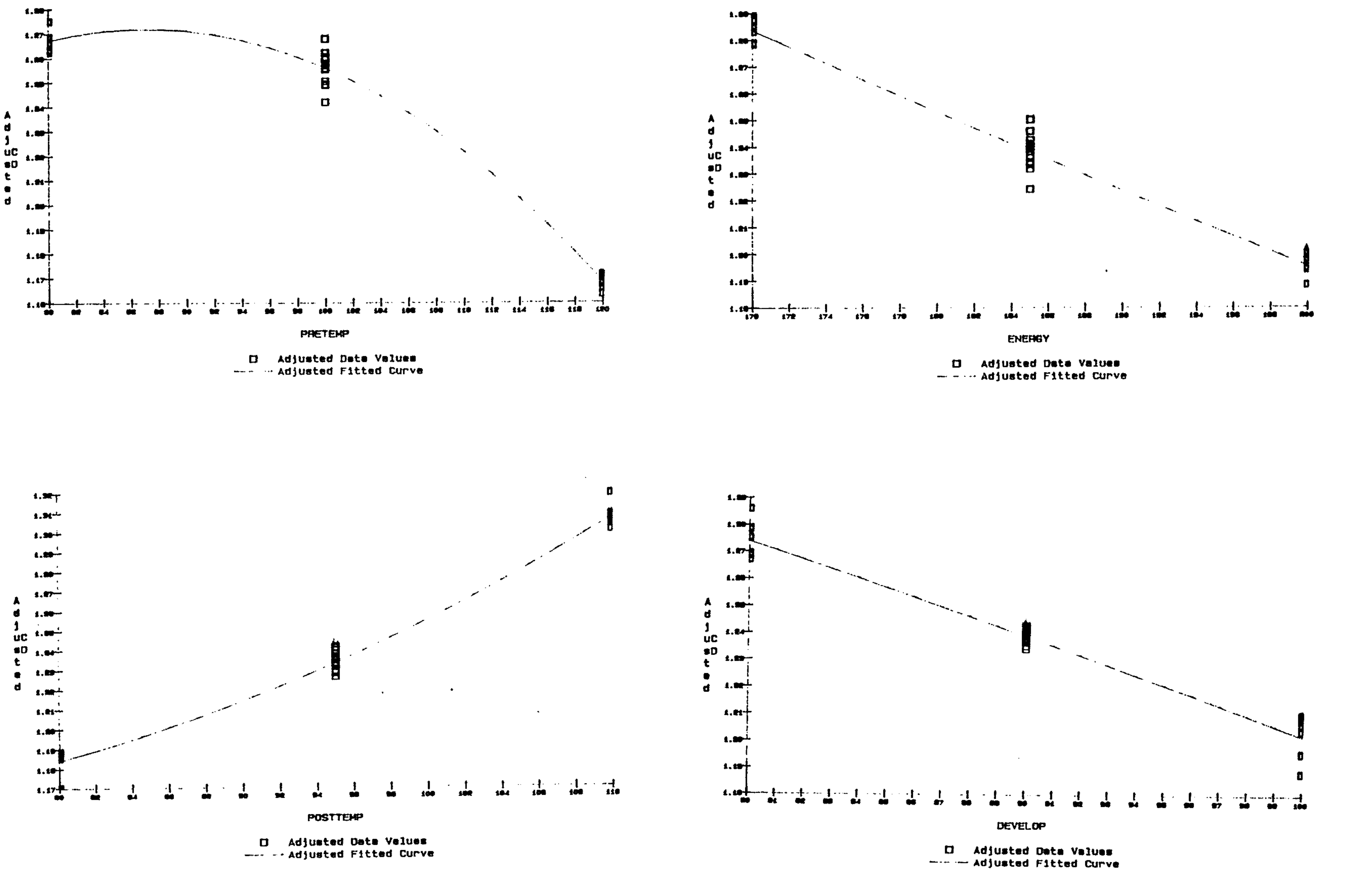

Figure 5: Effects of Prebake Temperatrue, Exposure Energy,
PEB Temperature and Development Time on CD.

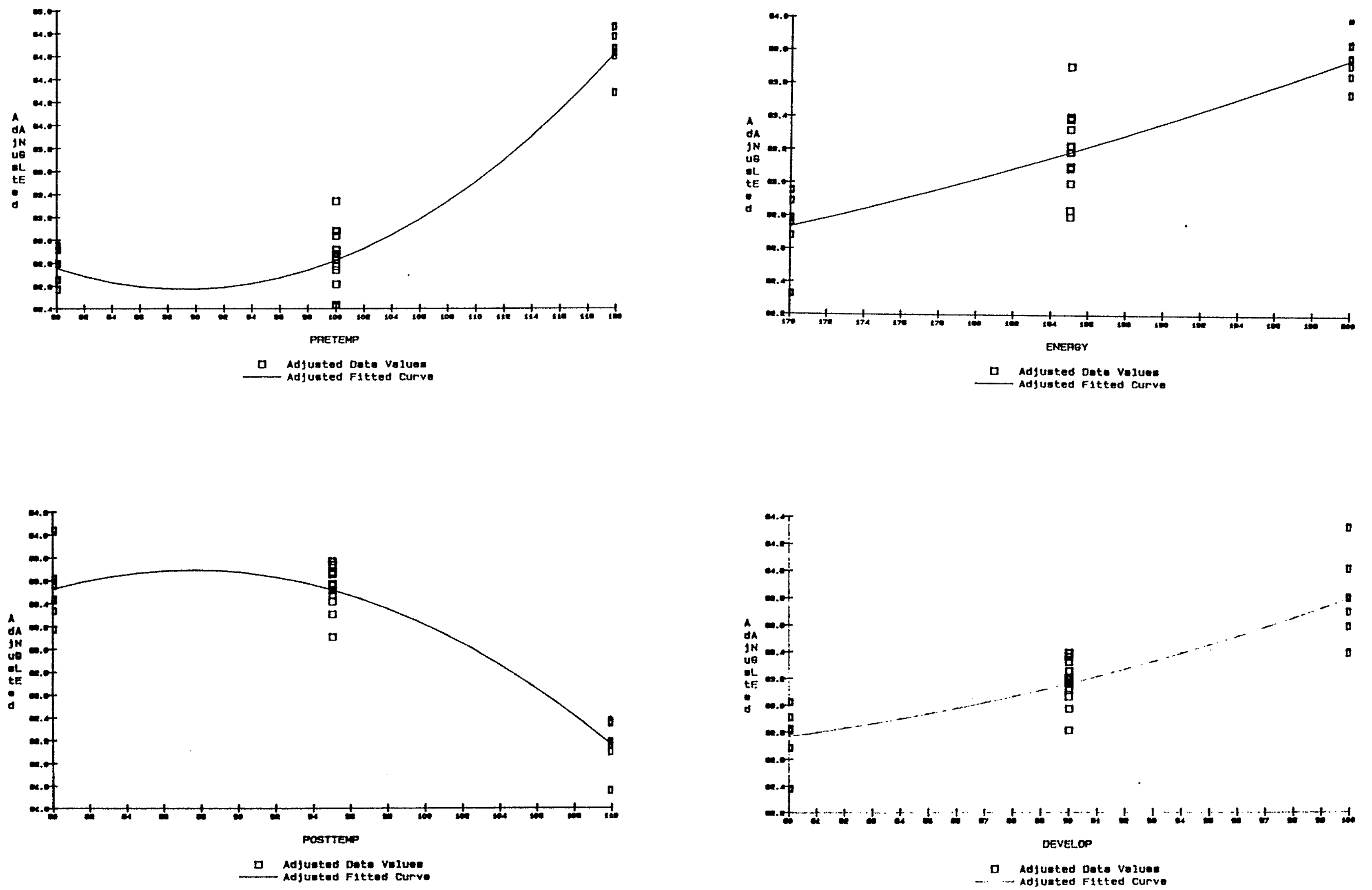

Figure 6: Effects of Prebake Temperatrue, Exposure Energy, PEB Temperature and Development Time on Sidewall Angle.

Linear relationships were seen between exposure energy and post exposure bake temperature and development time with the response of critical dimension. For the exposure energy and post exposure bake temperature, they are direct related to each other, while the exposure energy and development time have an indirect relationship. Therefore, if the exposure energy used was too high, beside shorter development time, higher post exposure bake temperature could also help solved the overexposure problem. From this, it could be drawn that the relation between post exposure bake temperature and development time were indirect to each other. From the RS/Discover analysis, it was also found that their relation was linear.

WEAKNESSES/BUGS IN PROLITH/2

During the usage of this software, several "bugs" were found. One occurred using a mask pattern of a space. After exposure, the resist would never clear no matter how long the development time was. There appear to be some error in the graphics program. The second error found was in the multiple run mode when development time was used as an input variable and resist linewidth was the output. Different linewidths were resulted each time the simulation was run, even for identical inputs.

CONCLUSION

PROLITH/2 is a new software which can simulate standard microlithographic processes. For the aerial image formation, the effects of exposure tools properites were studied on the aerial image log slope. It was found that larger NA, smaller coherence, less defocus, and little flare could improve the quality of the image. For coherence, defocus, and flare, the effects on the image log slope were linear. For NA and nominal linewidth, the effects were also quadratic. For the resist characterization, the effects of process variations were studied on the CD and sidewall angle of the resist profile. Increases in exposure energy, prebake temperature, development time but decrease in PEB could reduce the critical dimension of the resist. Exposure energy and development time affect CD linearly, while prebake temperature and PEB temperature's effects were quadratic.

ACKNOWLEDGMENTS

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REFERENCES

[1] FINLE Technologies, PROLITH/2 User's Manual, June 1990.
[2] W. M. Moreau, Semiconductor Lithography; Principles, Practices and Materials, (Plenum Press, New York, 1988).