Model Development for Image Reversal Resist Lithography

Charles Feng, Ben Keppeler, Jerry Wang, and Alice Fischer-Colbrie
Microwave Technology Division
Hewlett-Packard Company
Santa Rosa, California

ABSTRACT

The variation due to batch-to-batch inconsistency and aging can be a major process control issue for image reversal resist. We experimentally found that the dose-to-activate and the develop-to-clear time can be used to characterize both the batch-to-batch variation and resist aging. Using simplifying assumptions, we have developed a new mathematical model that correlates both resist linewidth and undercut with basic resist characteristics and processing conditions. This model greatly simplifies the resist qualification process and saves engineering time.

INTRODUCTION

Metal lift-off process plays an important role in the metallization of GaAs IC's since they account for about half of the lithography steps. In our wafer fab, image reversal (IR) resist is used for all lift-off layers. The chemistry of the image reversal resist was described by Buhr et al. [1]. Image reversal is achieved by crosslinking of Novolak resin. The crosslinker is activated by the acid that is generated photolytically. The process flow consists of resist coating and softbake on a track, image exposure using a stepper, reversal bake (also called post exposure bake), flood exposure, and a spray puddle develop [1, 2].

Due to the complexity of the resist system, the photoresist from different batches was usually not consistent enough to maintain the desired linewidth (CD) control. Photoresist from the same batch may change its characteristics dramatically due to aging. We experienced those problems when switching from one batch to another. The resist profile changed so much that metal could not be lifted, and the litho process needs to be regularly adjusted. The qualification of resist and maintaining process control are very time-consuming.

In this paper, we have identified some resist properties that are easy to measure and can be used to characterize the resist batch-to-batch variations and the resist aging. We have developed a mathematical model that correlates those resist properties and process variables to both resist CD and undercut (see Fig. 1), simplifying the resist qualification and process control.

Fig. 1 Reentrant resist profile for metal lift-off process
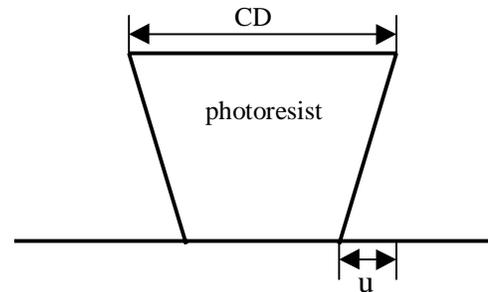
RESIST VARAITIONS

We used a dyed IR resist stored in a refrigerator per manufacturer's specification. In the following discussion, we will designate the resist variation from different batches as batch-to-batch variation, and the changes over time for the same batch as resist aging.

In order to characterize batch-to-batch variation and resist aging, we looked at variables such as resist thickness, properties in positive tone such as dose-to-clear Eo, and develop-to-clear time t_{d2c}, and in negative tone such as dose-to-activate Ea, for different batches and within a batch over time. Dose-to-activate Ea (also called interface gel dose), is the minimal image exposure dose that generates minimal amount of photoacid to activate crosslinking reactions. Develop-to-clear time t_{d2c}, is the minimal development time that just makes the wafer clear of resist. The samples we used for t_{d2c} measurement were prepared by first coating a Silicon wafer with 1.3 um IR resist, followed by post exposure bake and develop.

Table 1 lists the Eo, Ea, and t_{d2c} from different batches of resist. Both Ea and t_{d2c} vary as much as 77% and 50%, respectively, and we will see

that they dramatically affect both CD and u. Eo showed a large batch-to-batch variation. However, since the flood exposure dose is about three times the dose-to-clear and the resist in positive tone is over exposed, its variation does not affect the linewidth and undercut. We found no obvious resist thinning or thickening over the shelf time for this resist. Similarly the resist thickness from different batches was relatively constant.

Table 1. Resist Characteristics for different batches of dyed resist

Batch #	571	681	6D1
Eo(mJ/cm^2)	2100	1500	1463
% change* in Eo		-28%	-30%
Ea (mJ/cm^2)	113	213	200
% change in Ea		+88%	+77%
t_{d2c} (sec)**	160	115	240
% change in t_{d2c}		-39%	+50%

Note *: % change is based on resist batch 571.
**: t_{d2c} is the initial value from each batch.

Table 2 lists changes in t_{d2c} over time at ambient conditions for four different bottles of resist from the same batch. The first three bottles had the same initial t_{d2c}, but t_{d2c} increased with time for as much as 87% from its initial value. The last bottle after being in refrigerator for 5 months had an initial t_{d2c} of 165". This showed that the resist was slowly aging even under refrigeration. The Ea did not change over time within the same batch.

Table 2. Resist aging within the same batch of resist

	Days on track	t_{d2c} (sec)	% change from initial
Dyed Resist			
1st gallon (o)*	initial	115	0
2nd gallon (68)*	2	115	0
	21	165	+43
	44	215	+87
3rd gallon (89)*	2	115	0
	20	215	+87
	50	215	+87
4th gallon (152)*	3	165	+43
	42	165	+43

Note: * the number in brackets denotes the number of days the resist was kept in refrigerators.

In summary, different batches of resist have variations in Eo, Ea, and t_{d2c}. For the same batch of resist, the t_{d2c} increases over the time at ambient temperature but no Ea change over time is observed.

MODEL DEVELOPMENT

Reentrant resist profiles are required for clean lifts. Both the linewidth and the undercut need to be controlled simultaneously. In this work, we chose image exposure dose E, and development time t_{dev}, to control the linewidth and the undercut because they are easier to adjust than other variables related to the post exposure bake process.

In this section, we developed a system of equations that relates resist linewidth and undercut to the process variables E and t_{dev}, and basic resist properties Ea and t_{d2c}. The following is a list of assumptions used :

1) $\quad R \propto 1/E^{\gamma}$ $\qquad$ (1)

The resist development rate R is inversely proportional to the exposure dose with exponent γ. We reason that that more crosslinking of the resist matrix will decrease the development rate, and higher exposure dose will generate more photoacid and therefore there will be more crosslinking. γ is related to a reaction order for crosslinking reactions.

2) $\quad \dfrac{\partial CD}{\partial t_{dev}} = -R_T$ $\qquad$ (2)

This equation says the linewidth CD measured at the resist top, changes over development time is controlled by the development rate at top of resist, R_T. Because the CD here is for resist linewidth, a negative sign is added on the right hand of the equation.

3) $\quad \dfrac{R_p}{R_B} = f_1(T_{PEB}, t_{PEB}, developer\ property)$ (3)

This equation indicates the ratio of development rate of resist in positive tone R_P, to the development rate of bottom resist R_B, is a function of post exposure conditions, the type of developer (with or without surfactant, etc.) and its concentration, but independent of resist batch-to-batch variations and aging. The resist at the film bottom is only partially crosslinked, its property would be much like the resist in the positive tone after the flood exposure. Therefore even though R_P could change dramatically because of batch-to-

batch variations and resist aging as indicated by the changes in t_{d2c}, the ratio of R_P / R_B would remain relatively constant.

$$\frac{R_a}{R_P} = f_2 (T_{PEB}, t_{PEB}, developer\ property) \quad (4)$$

This assumption is similar to 3). It says that the ratio of resist development rate at dose-to-activate, R_a, over R_P, is only affected by post exposure bake conditions, the type of developer and its concentrations, but independent of resist batches and resist aging.

5) $\quad R_T << R_B \qquad\qquad\qquad (5)$

Here we assume the development rate of the top resist is much smaller than that of the bottom resist. The dye in the resist creates a gradient in light intensity, therefore a gradient in exposure dose, and resist crosslinking. This is very critical to create the negative resist profiles.

Using the assumptions 1), 2), and 4) and noting

$$R_p = h / t_{d2c} \qquad\qquad (6)$$

where h is the resist thickness, we derived the following new relationship.

$$CD = CD_0 - N_{litho}^{-1} \times\ h \times f_2$$

$$N_{Litho} = \left(\frac{E}{E_a}\right)^{\gamma} \left(\frac{t_{dev}}{t_{d2c}}\right)^{-1} \qquad (7)$$

Where CD_0 is an integration constant. In the second part of the CD equation, h is the resist thickness, f_2 is only a function of temperature and time of post exposure bake, and the type of developer and its concentration (see assumption 4). Normally all those parameters are fixed once a process is set up. The N_{litho} is a dimensionless number which involves not only processing variables E and t_{dev}, but also the basic resist characteristics, Ea and t_{d2c}. The resist CD is now a monotonic function of N_{litho}. It means that if N_{litho} number is kept constant, many different combinations of E and t_{dev} will give the same CD. If we plot the resist CD versus the $1/N_{litho}$, we should get a straight line for resist CD from different batches, resist aging, exposures dose, and development times.

Next we establish the relationship between the resist undercut, u, and the process conditions. Using the photoresist segment development concept [3], we begin with the following relationship:

$$u = -R_T t_{dev} + R_B (t_{dev} - t_{d2c}) \qquad (8)$$

Then with assumptions 3) and 5), we derive the second new relationship of our model. This equation relates the develop time and the resist undercut as follows:
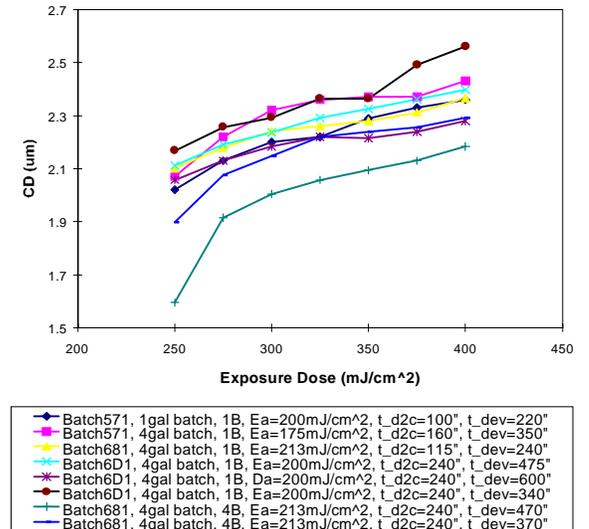
$$\frac{t_{dev}}{t_{d2c}} = a + \frac{u}{h} \times f_1 \qquad (9)$$

where a is a constant that depends on the quality of aerial image and the resist contrast. For ideal aerial image or infinity resist contrast, $a = 1$. The above equation shows that the resist undercut is a linear function of the dimensionless development time t_{dev}/t_{d2c}. With these two equations (Eq. 7 and 9) we can determine which E and t_{dev} to use for a targeted CD and undercut.

VERIFICATION OF THE MODEL

In order to verify equation (7), resist CD data were collected from different batches listed in Table 1 in a wide range of exposure and develop conditions (exposure dose from 250 mJ/cm^2 to 425 mJ/cm^2, and development time from 220 to 600 seconds). Figure 2 shows the CD vs. the exposure dose. Different lines represent the CD from a different development time or from different batches of resist though the same development time was used. It can be seen that the CD could be very different for the same E and t_{dev} due to variations in Ea and t_{d2c}. Therefore it can be tedious to locate the correct combination E and t_{dev} for a specific targeted CD and for a resist that has both batch-to-batch variation and aging effects.

Fig. 2 CD Data for Different Batches, Different Exposure Doses, and Different Develop Times
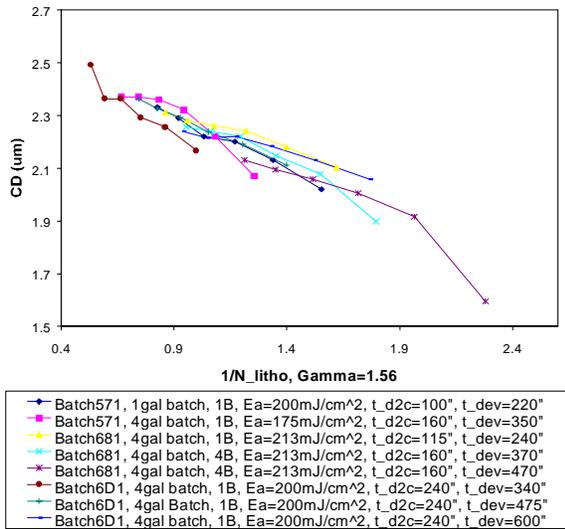

Batch571, 1gal batch, 1B, Ea=200mJ/cm^2, t_d2c=100", t_dev=220"
Batch571, 4gal batch, 1B, Ea=175mJ/cm^2, t_d2c=160", t_dev=350"
Batch681, 4gal batch, 1B, Ea=213mJ/cm^2, t_d2c=115", t_dev=240"
Batch6D1, 4gal batch, 1B, Ea=200mJ/cm^2, t_d2c=240", t_dev=475"
Batch6D1, 4gal batch, 1B, Da=200mJ/cm^2, t_d2c=240", t_dev=600"
Batch6D1, 4gal batch, 1B, Ea=200mJ/cm^2, t_d2c=240", t_dev=340"
Batch681, 4gal batch, 4B, Ea=213mJ/cm^2, t_d2c=240", t_dev=470"
Batch681, 4gal batch, 4B, Ea=213mJ/cm^2, t_d2c=240", t_dev=370"

Next we want to plot CD vs. N_{litho}^{-1}. We determined the γ value to be 1.56 by solving the

following nonlinear least square problem. $\hat{a}$ and $\hat{b}$ were found to be 2.61 and 0.35, respectively.

$$\min_{\hat{a},\hat{b},\gamma} \left\| CD_{Mes} - (\hat{a} - \hat{b}N_{litho}^{-1}) \right\|^2 \quad (10)$$

After the γ value was determined, we calculated the N_{litho} number for each data point in Figure 2 and plotted the CD vs. N_{litho}^{-1} in Figure 3. All the CD lines in Figure 2 fall closely on a single straight line as predicted by Eq. (7), showing resist CD is a linear and monotonic function of N_{litho}^{-1}.

Fig. 3 Generalized Relationship between resist CD and the dimeshionless N_litho

Batch571, 1gal batch, 1B, Ea=200mJ/cm^2, t_d2c=100", t_dev=220"
Batch571, 4gal batch, 1B, Ea=175mJ/cm^2, t_d2c=160", t_dev=350"
Batch681, 4gal batch, 1B, Ea=213mJ/cm^2, t_d2c=115", t_dev=240"
Batch681, 4gal batch, 4B, Ea=213mJ/cm^2, t_d2c=160", t_dev=370"
Batch681, 4gal batch, 4B, Ea=213mJ/cm^2, t_d2c=160", t_dev=470"
Batch6D1, 4gal batch, 1B, Ea=200mJ/cm^2, t_d2c=240", t_dev=340"
Batch6D1, 4gal Batch, 1B, Ea=200mJ/cm^2, t_d2c=240", t_dev=475"
Batch6D1, 4gal batch, 1B, Ea=200mJ/cm^2, t_d2c=240", t_dev=600"

Eq. (9) indicates that if we keep the undercut the same, and for fixed resist thickness, post exposure bake conditions, developer type, and developer concentration, the dimensionless development time must remain the same. In other words if we plot t_{dev} versus t_{d2c} for fixed undercut, we should get a straight line passing through the origin. This is proved in Fig. 4 (in the left column) where resist under cut is 0.25 um.

APPLYING THE MODEL

After the model is validated, we can solve two equations with two unknowns to determine the processing conditions. Once the required resist undercut is specified, the t_{dev}/t_{d2c} can be determined from Eq. (9). For a targeted CD, the N_{litho} value can be uniquely determined from Eq. (7) or using Figure 3. Then, E and

Fig.4 Development time as a function of develop-to-clear time
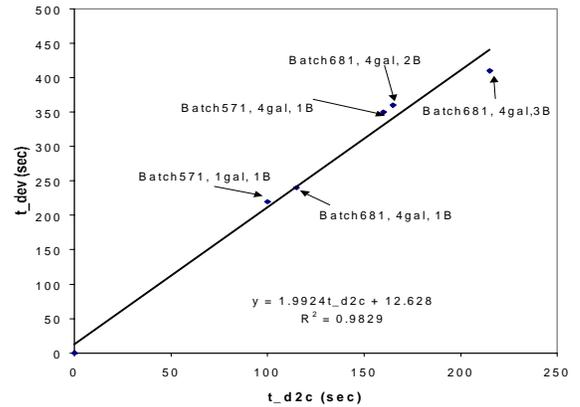
t_{dev} can be determined from the measured properties Ea and t_{d2c}. This dramatically reduces the number of tests including the time-consuming cross-sectioning. In addition, the model can be used to speedup the process development for other CD and undercut requirements. The above model has been used in production for more than a year in the GaAs Fab in HP. We have reduced engineering time for resist qualification by more than 50%. We also have saved a lot of test wafers by the new resist qualification procedure.

SUMMARY

We experimentally found that the dose-to-activate and the develop-to-clear can be used to characterize both the batch-to-batch variation and resist aging. Furthermore, we have developed a new mathematical model that correlates both linewidth and undercut with basic resist characteristics and processing conditions through dimensionless numbers. A new resist qualification procedure was developed based on this model. The new procedure greatly saves engineering time and test wafers.

REFERENCE
[1] G. Buhr, H Lenz, and S. Scheler, "Image Reversal Resist for g-line Exposure: Chemistry and Lithographic Evaluation", SPIE Vol. 1086, Advances in Resist Technology and Processing VI (1989).
[2] J. Wang, B. Keppeler, and E. Wong, " Evaluation of a New g-line Image Reversal Lift-off Process", GaAs ManTech Conference, 1993.
[3] M.P.C. Watts and M.R. Hannifan, "Optical Positive Resist Processing II, Experimental and Analytical Evaluation of Process Control,"Advances in Resist Technology and Processing II, Proc., SPIE Vol 539 (1985) pp. 21-28.