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Susan L. Morton, F. Levent Degertekin, and B. T. Khuri-Yakub

Citation: *Appl. Phys. Lett.* **73**, 2215 (1998); doi: 10.1063/1.122427

View online: <http://dx.doi.org/10.1063/1.122427>

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In situ ultrasonic monitoring of photoresist development

Susan L. Morton,^{a)} F. Levent Degertekin, and B. T. Khuri-Yakub
Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305

(Received 22 June 1998; accepted for publication 11 August 1998)

We have developed an *in situ* method to measure the change in thickness of photoresist during development. The phase of a high frequency ultrasound signal is monitored as it is reflected from the silicon/photoresist interface during resist development. The method was tested using a 1.5 μm film of Shipley 1811 resist. The total phase change during development of 19° was consistent with theoretical calculations at 280 MHz, and this change was used to obtain the resist thickness during development. The method was used to find the development rate of this positive-tone resist as a function of exposure dose in the 20–68 mJ/cm^2 range. As expected, there was an increase in development rate as the exposure time increased; this continued up to about 40 s of exposure, beyond which the rates were essentially unchanged. Measurements on a wafer with microelectronic devices ranging in topography from 0.10 to 1.0 μm show that the method is applicable to wafers with typical circuit topography. © 1998 American Institute of Physics. [S0003-6951(98)03341-5]

Once a lithographic pattern has been exposed onto a resist film, the pattern must be developed by etching away the portions of resist that are soluble in the developing solution after the exposure. It is important in subsequent processing that the remaining resist be as close to its original thickness and as etch resistant as possible. To optimally etch all of the soluble resist without significantly degrading the masking resist, it is important to determine the endpoint of the former reaction. Endpoint detection based on optical monitoring of the photoresist thickness has been applied for over a decade,^{1–3} but this measurement requires that the development solution be transparent to the incident light. The technique described here monitors the thickness change during development and provides process endpoint detection, without the necessity of an optically transparent development solution.

The method for monitoring changes in the reflection coefficient during resist processing was described previously.⁴ Briefly, an 8 μm thick zinc oxide (ZnO) film is deposited on a sapphire buffer rod which is placed in contact with the back side of the wafer. The ZnO transducer is excited with a high voltage spike, launching a longitudinal wave that is coupled to the silicon wafer. The reflected signals from the silicon/photoresist interface are converted to an electrical signal by the transducer and digitized. The phase is determined by subtracting the phase of the first two reflections, eliminating systematic effects unrelated to resist thickness.

The reflection coefficient for a longitudinal plane wave incident from a medium on a layer is calculated using classical reflection theory.⁵ This expression for the reflection coefficient is shown in Eq. (1). We expect a phase change in the reflected signal as the photoresist thickness changes; this change is expected as a result of thin film interference effects:

$$R = \left(\frac{\left(1 - \frac{r_1}{r_3}\right) \cos k_2 L + j \frac{\rho_2 c_2}{r_3} \sin k_2 L}{\left(1 + \frac{r_1}{r_3}\right) \cos k_2 L + j \frac{\rho_2 c_2}{r_3} \sin k_2 L} \right). \quad (1)$$

To demonstrate this development process sensor, an 8 in. wafer was spin coated with Shipley 1813 photoresist to a thickness of 1.5 μm . The coated wafer was prebaked in a 90 °C oven for 30 min and then exposed for 45 s with a Kasper mercury vapor lamp (dose=61 mJ/cm^2). After approximately 50 s of obtaining background noise data, the developer was applied to the wafer; the developer consisted of a 1:1 volume mixture of Microposit developer concentrate and water. The resulting phase change versus time at a frequency of 283 MHz is shown in Fig. 1. Endpoint can be seen to occur at about 75 s, with an average development rate of about 0.1 $\mu\text{m}/\text{s}$. The phase change of 19° agrees well with the theoretically expected phase change for removal of 1.5 μm resist at this measurement frequency. It should be noted that besides the phase change due to resist removal, there is an initial change resulting from the addition of the developer solution. This instantaneous change was measured to be about 7° at 283 MHz and has been subtracted from the mea-

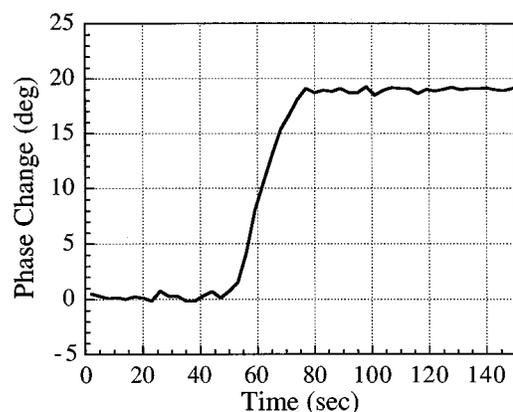


FIG. 1. Phase change vs time during development of a 1.5 μm resist film.

^{a)}Electronic mail: smorton@macro.stanford.edu

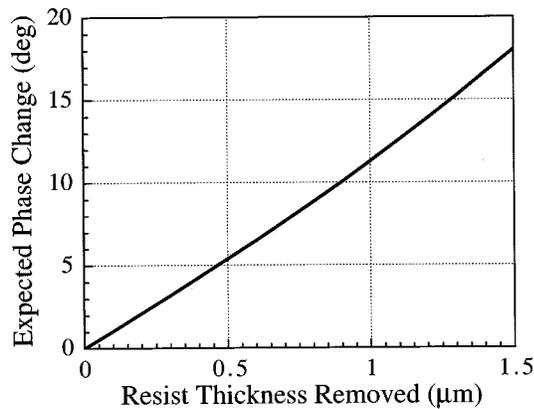


FIG. 2. Expected phase change vs thickness of resist removed.

measurements. Figure 2 shows the results of calculating the expected phase change versus thickness of resist removed from Eq. (1). From this plot, the thickness of the resist can be determined during development. Figure 3 shows the results of this inversion. As can be seen from the plot, the development rate falls off with thickness removed. This is probably a result of absorption of the exposing light as it travels through the resist, causing the exposure levels to drop closest to the wafer. Two other locations were also developed on the same wafer with similar results; there was an 18° phase change at one location and a 19° change at the other with development rates similar to that at the original location.

To measure the difference in development rate that results from different exposure levels, six 8 in. wafers were separately spin coated with $1.25\ \mu\text{m}$ of Shipley 1811 resist, prebaked at 90°C for 30 min, and then exposed using a Kasper aligner for varying lengths of time from 15 to 50 s, or doses of 20–68 mJ/cm^2 . Figure 4 illustrates the results of these experiments in terms of thickness of resist versus development time. The dissolution rate increased as the exposure dose increased from 20 to 55 mJ/cm^2 , but then remained unchanged above about 55 mJ/cm^2 . The plot shows thickness change versus time of development for exposure doses of 20, 27, 34, and 55 mJ/cm^2 . For clarity, the results of the 40 and 68 mJ/cm^2 exposures were not included in the plot. Figure 5 shows the calculated development rates plotted versus exposure dose, this time including the 30 and 50 s exposures (40 and 68 $\text{mJ}/\text{sq cm}$, respectively). As seen in Fig. 5, the rates increased from 0.04 to 0.155 $\mu\text{m}/\text{s}$ as the exposure dose

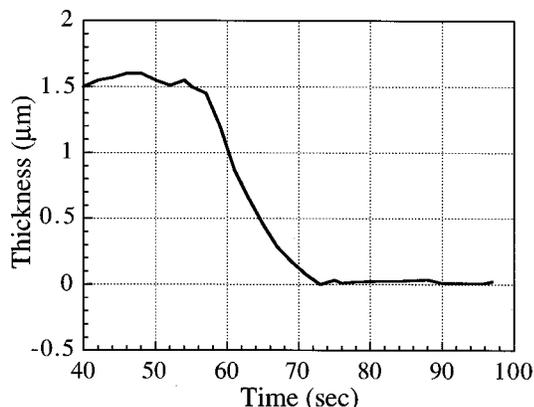


FIG. 3. Inverted thickness of resist during development.

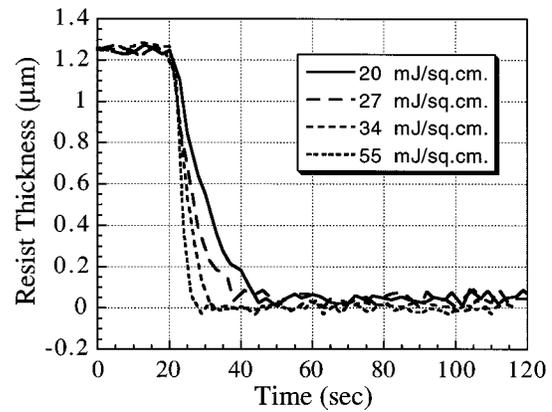


FIG. 4. Resist thickness vs time during development of films exposed with varying doses.

increased from 20 to 68 mJ/cm^2 . The rates were measured by fitting a curve to the linear portion of the thickness versus time curve and determining the slope. The filled circles in Fig. 5 represent the actual datapoints while the solid line represents a curve that was fit to the data. As can be seen, once a critical exposure dose was reached, the resist began to overexpose; in a manufacturing setting, any additional exposure beyond this critical dose would decrease manufacturing throughput without any beneficial effect on feature size.

One consideration in designing a sensor to monitor development is whether or not topography on the wafer will interfere with the measurement. In order to test the sensor in this situation, it was used to monitor development of resist spun onto a 4 in. wafer patterned with PMOS test devices ranging in topography from 0.10 to $1.0\ \mu\text{m}$. The resist thickness was $1.25\ \mu\text{m}$ and, as before, the resist was prebaked in an oven for 30 min at 90°C and then exposed for 40 s using a Kasper aligner. The total phase change once the resist was completely removed was about 15° , as expected from theory for a $1.25\ \mu\text{m}$ film measured at 283 MHz. The resulting thickness change versus development time is plotted in Fig. 6 with a calculated average development rate of $0.167\ \mu\text{m}/\text{s}$. It is concluded that the sensor can monitor development with three-dimensional topographical dimensions on the order of the thickness of the resist film. This indicates that the measurement is applicable to monitoring resist development during integrated circuit semiconductor processing. Another consideration is the sensitivity of the measurement to devel-

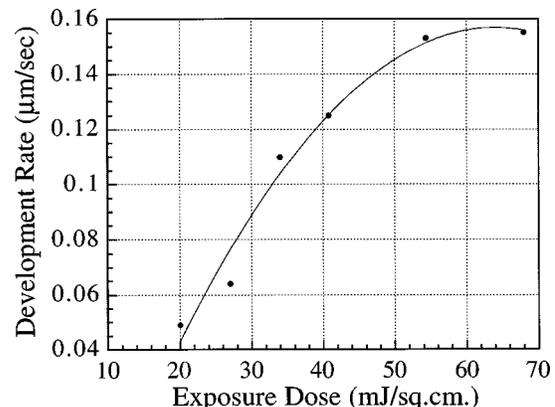


FIG. 5. Average development rate vs exposure dose.

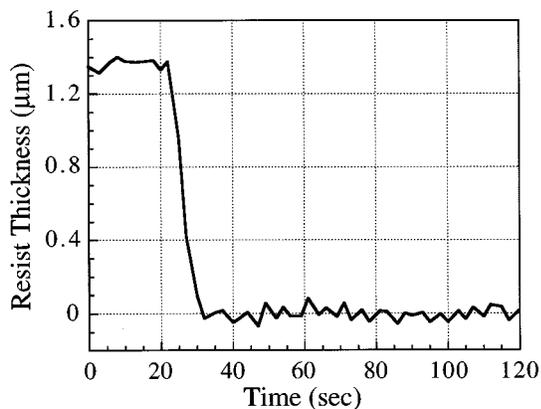


FIG. 6. Resist thickness vs development time on wafer with three-dimensional topography.

opment of a resist pattern instead of the blanket film removal studied above. Given that the noise level of the measurement is approximately 1° , our calculations indicate that the transducer can monitor development of a pattern where the total area developed is greater than $1/20$ of the original area. Thus, if a pattern of lines is developed the change in phase will be measurable if the total area of the lines removed is greater

than $1/20$ th of the original area of resist coating.

We have developed a sensor to monitor the thickness of photoresist during lithographic development. This has been accomplished on a bare silicon wafer and on a wafer with three-dimensional topography on the order of the resist thickness. The sensor can also differentiate between development rates as was demonstrated previously. This technique can be applied to *in situ* monitoring of lithographic photoresist development in a manufacturing setting.

The authors would like to acknowledge the funding support of DARPA and project monitoring by the Air Force Office of Scientific Research under Grant No. F49620-95-1-0525.

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