Photolithography for Minimal Fab System

Sommawan Khumpuang* a) Member, Hitoshi Maekawa* Non-member
Shiro Hara* Non-member

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Minimal Fab System Photolithography has been developed for wafer patterning process without the requirement of a cleanroom. It consists of minimal resist coater, minimal maskless UV exposure, minimal mask aligner and minimal resist developer. We have proved in practice that the spin coating using minimal resist coater for a 0.5-inch wafer gives the identical result of resist thickness compared with 4-inch wafers without changes to a higher rotational speed. The minimal maskless UV exposure using Digital Light Processing (DLP) confirms that only one LED light source with the light intensity of 150 mW/cm² can expose over a 0.5-inch wafer in a few minutes. The minimal mask aligner is developed for a high speed exposure within 5-20 seconds. The aligner also uses a LED light source that can produce the light intensity of 14 mW/cm². The present photosensitive resolution for the maskless UV exposure and the mask aligner are 1 µm and 2 µm, respectively. The minimal developer has minimized its consumption of developing agents. Due to the surface tension, a volume of developing agent is kept on the wafer surface for slowly spinning to stimulate the developing process. The developing time is 20% saved from that of the conventional puddle development.

Keywords: Minimal Fab System, clean room free, photolithography, edge bead removal

1. Background

In manufacturing process of an integrated circuit (IC), photolithography is the compulsory operation where the function and complexity of each IC are designed and determined at this level. Photolithography requires a variety of physical and chemical processes performed on silicon wafer. There has been more than a decade that fundamental lithography process is established where the process on larger wafer and smaller design rule is currently main development in Semiconductor research and industrial sections(1). The advance lithography process has limited only for 3 inches wafer and/or above.

The development of photolithography comes along with the development of cleanroom and the increasing of process space and wafer size. In the cleanroom, the manufacturing lines are pressurized with filtered air to remove particles and the operator must wear cleanroom suits to protect the devices from contamination. It is obviously that not only photolithography which holds the top amount of the semiconductor manufacturing cost but also the clean room. The cleanliness class of 0.1 is the requirement when addressing the feature size 0.5 µm-0.25 µm which is in the range of conventional UV wavelength for exposure in photolithography method(2). In this work, the cleanliness class of 0.1 for patterning the photosensitive machines lined up in a common office space. Minimal Fab System employs the extremely economical and low energy consumption system for microfabrication of device on 0.5-inch silicon wafer. The system for particle free lithography process consists of a clean carrier, a clean wafer transfer system and minimal lithography machines. Figure 1(b) illustrated the clean carrier named minimal shuttle

which is fabricated from UV cut material and used for isolating the silicon wafer from the surrounding air and contaminations.

Figure 1(c) shows the minimal machine and cleaned wafer transfer system named Particle Lock Air-tight Docking (PLAD). PLAD is functioned to lock and unlock a minimal shuttle using the magnetic switch mechanism and to transfer the wafer between the carrier and the machine process unit. The advantage of using magnetic switch mechanism is to diminish the particle from scratching by the interfacing parts of the shuttle and PLAD. Inside the transfer room of PLAD, the down-flow clean air applied through punching plates makes lamina flow through the transfer room and particle free space.
Photolithography for Minimal Fab System (Sommawan Khumpuang et al.)


2. Cleaned Wafer Transfer System

The developed 0.5-inch wafer clean system consists of 3 components; PLAD, shuttle and process room to achieve the clean level as well as super cleanroom. The most important component is the wafer transfer system (PLAD) since it has to be interfaced with the atmosphere while docking the shuttle. The particle counting experiment for the PLAD is performed with the experimental setup as shown in Fig. 2(a). Figure 2(b) illustrates the 3 steps of counting particle imitating the actual use of the PLAD.

The experiment is set by inserting the measuring tube of particle counter to the center of the PLAD. The inlet of clean air on top of the PLAD is used to supply the clean air while PLAD is open. The clean air flow is laminated by flowing through triple punching plates. The particle counting is performed for 300 s and the counting cycle is 6 s (4 s measuring and 2 s resting). The experimental sequence is; STEP 1: clean air valve is closed and PLAD is opened, STEP 2: PLAD is closed and clean air valve is opened, STEP 3: PLAD is opened and clean air valve is closed. It is obvious that the PLAD has to be free of particle in the step 2.

We have proved the clean level of our developed PLAD by the experimental result shown in Fig. 3. As a result, the particle in PLAD dropped from class 10000 to class 0.1 within 20 s when clean air is supplied to the PLAD. The clean level will remain until the PLAD is opened again. The experiment confirms that our PLAD is the novel invention to eliminate the needs of expensive cleanroom.

3. Minimal Fab System Lithography

The Minimal Fab System lithography consists of minimal resist coating machine, minimal maskless UV exposing machine, minimal mask aligner and minimal resist developing machine.

3.1 Minimal Resist Coating Machine and its Process

Figure 4 describes the process chamber of minimal coating machine with an image of resist coated wafer including the edge bead removal. There have been a number of issues(3)(4) concerning the spin coating phenomena of small chip, i.e., one inch or below. In this work, we mainly state the problems that the small substrate prepared from dicing has 2 effects in spin coating; the edge beads and geometrical effects. The edge beads are due to the viscosity of the fluid and surface tension which can be partially controlled by spin recipe. Due to the fact that the edge bead is inversely dependent on spin speed(5), as shown in Figure 5, very high spin is required when the photoresist is coated on a small diameter substrate.

The plot gives trend for a 0.5-inch wafer coating of 10 times over the speed of coating on 12-inch wafer (300 mm). The geometry effects depend on the evaporation of rate at the periphery of substrate(6). The substrate with rectangular shape causes the waveform pattern in the film at the corner.

After the resist is applied on the substrate, the resist spreads by spinning in the form of Newtonian finger as illustrated in Fig. 6(a). The air friction is increased at the corner resulting in an increased evaporation rate and the resist at the edge corner dried before close. The clean air flow is laminated by flowing through triple punching plates. The particle counting is performed for 300 s and the counting cycle is 6 s (4 s measuring and 2 s resting). The experimental sequence is; STEP 1: clean air valve is closed and PLAD is opened, STEP 2: PLAD is closed and clean air valve is opened, STEP 3: PLAD is opened and clean air valve is closed. It is obvious that the PLAD has to be free of particle in the step 2. We have proved the clean level of our developed PLAD by the experimental result shown in Fig. 3.
Fig. 4. Images of process unit for resist coating of a 0.5-inch wafer with enlarged image of photoresist coated wafer and showing a uniformed resist coating result.

Fig. 5. Plot of predicted spin speed required to coat for 1 µm-thick positive photoresist on a 0.5-inch wafer.

Fig. 6. Schematics of photoresist (PR) coated on a square substrate where PR starts to be spread over by initial spin speed and following by spinning off PR from the substrate. The process leaves the reservoir at the thick corner dried first.

Fig. 7. Schematic of solid-liquid-gas interface and the contact angle.

We have solved the problem by preparing circular substrate with fine beveling and proved in practice that the spin coating for a 0.5-inch wafer gives the identical result of resist thickness compared with 4-inch wafers without changes to a higher speed rotation. Beveling of the edge or periphery of the substrate is to smooth the film surface as the bevel angle will neutralize the contact angle and at the solid-liquid-gas interface as described in Fig. 7. The second issue for spinning photoresist on a small substrate is that why the centrifugal force dependent on the diameter of the substrate has no influence in our spin-coating system. The centrifugal force is functioned to spread resist over the substrate until exceeded resist has been removed (where typically only 5% of the liquid dispensed remains on the substrate). We take the advantage of small area substrate, a drop of photoresist with volume of only 50 µl immediately covers the entire substrate surface area thus the high centrifugal force is not required for spreading liquid over the substrate. The fine beveling assists the removal of the exceeded resist more quickly than that with rough beveling, therefore the uniform film on the substrate can be approached with the same spinning speed of 4 inch wafers. The minimal resist coater is designed for maximizing the process area on the 0.5-inch wafer. The edge bead removal (EBR) is performed at 0.3 mm from the edge which makes the edge exclusion of 0.5 mm for 0.5-inch wafer coating. After the spin coating is finished, the wafer is baked with at the temperature of 90°C for 60 s. It is noted that the power consumption of the minimal resist coating machine is maximum 150 W.

3.2 Minimal UV Exposing System

The exposing system developing trend is totally relevant to the wafer size and design rule while the large the system is, the suitability for consuming the equipment in the research field is much less than the volume manufacturing purpose. This is because of the cost and the energy and material consumption. We have developed a compact size of UV exposing machines where the light source is only an LED to minimize the power consumption. Since the exposure area is only about a square centimeter, a small condenser lens is used. Our minimal UV exposing system consists of a minimal maskless exposing machine using Digital Light Processing (DLP) method and a minimal mask aligner. The scanning projection mechanism is described in Fig. 8(a).

The advantage of maskless exposure system is that the designed pattern can be directly exposed on the scanning substrate without the requirement of the photomask but the raw drawing data which is at last converted to bitmap data before exposure as shown together with an image of resulting PR pattern in Fig. 8(b). For maskless exposing machine, the LED light source is producing the light intensity of 150 mW/cm². The 0.5-inch wafer can be exposed for the entire area in 5-20 minutes depending on the thickness of photoresist. The DLP exposing machine is a dynamic exposing.
Photolithography for Minimal Fab System (Sommawan Khumpuang et al.)

3.3 Minimal Developing Machine and its Process  We have designed the minimal developer for minimizing its consumption of developing and rinsing agents. The novel development process named spin-development is applied to optimize the developing time and pattern resolution. Figure 9 illustrated the actual development process flow.

The detail of each step is explained below
Step 1: 0.5-inch wafer is chucked on the spin unit (Fig. 9(a))
Step 2: 0.4 ml of developing agent is dispensed to the wafer surface. The nozzle is set above the center of wafer for 4 mm (Fig. 9(b))
Step 3: Due to the surface tension, the volume of dispensed liquid is kept on the wafer surface while slowly spinning speed is applied to stimulate the developing process. From the experimental result, the maximum height of volume liquid at 4 mm is remained on the wafer during the development with the speed up to 300 rpm with none of the developing agent is spun out of the substrate. Therefore, the process is performed with the spinning speed of 300 rpm for 20 s (Fig. 9(c)).
Step 4: Repeat of step 2 while the volume of fresh developing agent dispensed is reduced to 0.2 ml. This is to let the fresh agent to replace half volume of the reacted agent and makes the patterning resolution better
Step 5: Repeat of step 3 for 15 s.
Step 6: Dispense Rinsing liquid (de-ionized water) for 1 ml while spinning at 800 rpm for 15 s (Fig. 9(d))
Step 7: Spin dry the wafer with 4500 rpm for 15 s (Fig. 9(e)).
Step 8: stop the spinning and unchuck the wafer (Fig. 9(f)).

As shown in Fig. 10, the volume liquid could be kept on the 0.5-inch wafer with high volume of developing agent per developing area. Therefore the fresh development process with such a small volume of the liquid is approached with this method. The dynamic development without requirement of any external system where the exposing size of ~1.0×0.5 mm² is spotted on a scanning wafer. The resolution of our maskless exposure system from the projection imaging side, resolution is determined by the wavelength of the imaging light (λ) and the numerical aperture (NA) of the projection lens using the formula resolution (R) = kλ/NA where the process factor (k) is 0.6, λ of the LED is 365 nm (i-line) and NA of the lens is 0.4. The calculated resolution of our system is 0.5475 μm for the exposure and the currently controlled result at the process line is about 1 μm lines and spaces (L&S). Minimal mask aligner has been developed for a high speed exposure. The mask aligner also uses a LED light source producing the light intensity of 14 mW/cm² and the entire wafer area can be exposed within 5-20 seconds. The power consumption of the minimal maskless exposure system is at the maximum 400 W where that of the minimal mask aligner is within 150 W. The present photoresist feature for the mask aligner has the resolution of 1 μm where the controlled result at the process line is about 2 μm of L&S. The photomask itself can be fabricated within the same production line as the wafer using the same wafer carrier and wafer transfer system of Minimal Fab since both mask and wafer are designed to have the same size. The mask aligner supports both contact and proximity printing between wafer and the photomask. However, the contact printing can be performed with minimum damage since the contact pressure between mask and wafer is monitored and controlled. Moreover, the contaminated mask can be cleaned using minimal wet cleaning machine.

Fig. 8. Schematic of DLP exposing component and resolution of the CAD data compared with the resulting pattern

Fig. 9. The process flow of spin-development using minimal developing machine

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Fig. 10. Image of liquid volume kept during spinning process, and the schematic described the liquid shape changes with the spin. $\theta_{\text{max}}$ is the maximum contact angle where the surface tension at the edge of wafer is not overcome by the center of mass of the spun liquid.

Fig. 11. Microscopic image of resist patterning result from Minimal Fab System Lithography performed outside a cleanroom with edge exclusion of 0.5 mm.

Stimulation is to spin the wafer with the slow speed where the surface tension is still holding the liquid volume on the wafer. This process will let the produced nitrogen gas from reaction between developing agent and the photoresist move away from the surface of the substrate and let the fresh developing agent come into reaction.

The developing agent employed in this process is a tetramethyl ammonium hydroxide (TMAH) based solution (NMD-3 2.38%, Tokyo Ohka Kogyo Co., Ltd.). With this method, the developing time is 20% saved from that of the puddle development on a 4-inch wafer. After the resist pattern is inspected under the microscope, the hard baking process is performed at the temperature of 120°C for 300 s.

4. Result and Discussion

The lithography result shown in Fig. 11 confirmed that the edge bead removal of the resist can be controlled within 0.5 mm and the patterned resist is free from particles over 0.3 µm due to the observation by the optical microscope although the entire processes are performed in usual office space. Figure 12 illustrates an SEM photograph of the patterned photoresist for line and space of 2.16 µm each (4 pixels).

Fig. 12. SEM photograph of the photoresist patterned by minimal fab system lithography

The development result from the spin-development method with and without refreshment of the developing agent compared with the conventional puddle development are illustrated in Fig. 13(a), (b) and (c) respectively. In addition, all the baking processes during the photolithography are performed with energy saving hot plates of only 25 W where the entire machine consumes the power only maximum 150 W.

5. Conclusion

Since the lithography process using spin coating and developing of the photoresist has been one of the most mature process in semiconductor manufacturing, the process development has been slow down and people aim to investigate only new exposure technologies to realize a few tens nanometer feature size of resist patterning. This tends to keep the market of high volume but low variation of the production. This work has reported the new trend of a lithography system for high variation and supports the volume markets up to 450 k chips per annual production. Our developed Minimal Fab system for 0.5-inch wafers is an optimal system for the needs of low and medium volume market of the semiconductor devices, sensors and micromachining system. The lithography is suitable and flexible to the development of new devices with very low cost, and low consumption of materials, energy and time.

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References


Sommawan Khumpuang (Member) received MSc. in Mechanical Engineering from University of Bristol, UK in 2002. She studied Ph.D in silicon processing technologies and synchrotron radiation lithography at Ritsumeikan University, Japan and received her Ph.D in 2006. She joined the Microsystems Materials Laboratory of IMTEK, Germany as a post-doctoral fellow in 2007 for a research in Microneedle and its replication project of Alexander von Humboldt foundation. In 2009, she has become a research at BEANS laboratory carrying the research in electronic textiles field and her present carrier started from 2011 is a researcher at National Institute of Advanced Industrial Science and Technology, AIST. Her current research involves with the development and implementation of Minimal Fab System and its process technology.

Hitoshi Maekawa (Non-member) was born in 1963. He received B.E. (1986), M.E. (1988) and Ph.D. (1997) degrees in control engineering from the Tokyo Institute of Technology, Japan. He joined the Mechanical Engineering Laboratory, Ministry of International Trade and Industry (MITI), in 1988. From 1997 to 1998, he was a postdoctoral visiting researcher at the University of Utah, USA. Also he was a visiting researcher at Tampere University of Technology, Finland in 2001. Since 2001, with reform of MITI's laboratories, he has been a senior researcher of the National Institute of Advanced Industrial Science and Technology (AIST). His research interests include the control of the dexterous multifingered hand, development and application of the finger-shaped tactile sensor, and material handling technology in minimal fab system.

Shiro Hara (Non-member) received his Ph.D in engineering from Waseda Univ. In 1989, he joined Waseda Univ. where he was an Assistant Professor. He was a special researcher, basic science program in Riken Institute since 1990. In 1993, he became a researcher of Electrotechnical Laboratory, MITI. He developed a local clean research system to find elemental cause of variations of electronic device characteristics. From 2001 to 2002, he joined R&D Association for Future Electron Devices as General Manager of R&D Department and Director of Planning Office. In 2007, he proposed the Minimal Fab concept to reduce an investment cost of a semiconductor factory into 1/1000. He is the minimal system group leader in AIST, METI. Also, he is the representative of Fab System Research Consortium of AIST. Now, he is the project leader of the national project “minimal fab”.

277 IEEJ Trans. SM, Vol.133, No.9, 2013