Masks for laser ablation technology: New requirements and challenges

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Laser ablation is used as a dry patterning process in which an intense beam of light from an excimer laser is used to pattern a material directly. This process has found extensive application in the microelectronics industry for patterning of polymer materials. A typical laser ablation tool is very similar to a conventional optical lithography projection tool; the primary difference is the wavelength and the intensity of the light used in the ablation process. Conventional chromium-coated quartz masks are incompatible with 1× laser ablation tools because the chromium layer is rapidly damaged. This paper discusses a mask technology which has been developed specifically for excimer laser ablation. The mask consists of a quartz substrate with a stack of dielectric films which have been selected for the laser ablation wavelength. Mask fabrication is accomplished with standard microelectronic processes and equipment. Such masks have been used in IBM manufacturing since 1987 and have met all process specifications such as resolution, defect density, and damage resistance.

Introduction

Laser ablation technology is a technique which has been developed over the past ten years for materials processing. The laser ablation process requires an intense ultraviolet light (λ = 193–351 nm) produced by an excimer laser [1–3]. Because of the high absorption of ultraviolet light and relatively poor thermal conductivity of many materials, particularly polymers, the energy is deposited in a very thin layer. Whenever the energy density, or fluence, exceeds the ablation threshold value for the material, chemical bonds are broken, fracturing the material into energetic fragments. The fragments are atoms, groups of atoms, ions, and electrons. Because the fragments leave the reaction zone as an energetic gas and solid debris, the ablation process resembles explosive evaporation of the material (**Figure 1**).

A unique property of this process is that most of the absorbed energy is carried off with the ejected material, so that there is little or no thermal damage to the surrounding substrate area. Another property of this process is that the ablation threshold of metals is significantly higher than that of polymers. In the case of patterning polymers over metals, the metal layer usually acts as an undamaged etch stop. By irradiating

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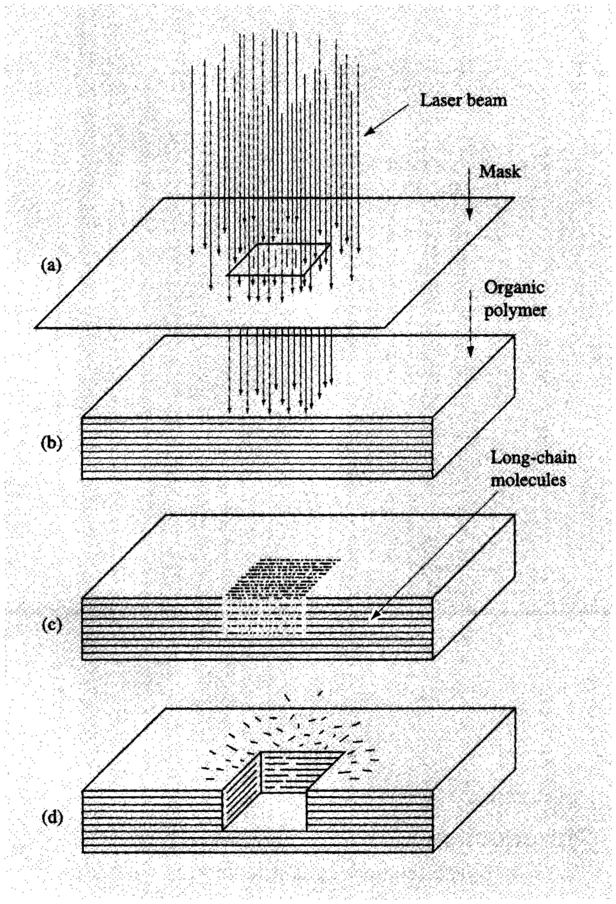

Figure 1

Sequential steps in the schematic illustrating the ablation process: (a) irradiation; (b) absorption; (c) bond breaking; (d) ablation.

a mask containing the desired pattern and projecting this image onto a material, precise patterns can be produced. This one-step process is therefore capable of replacing conventional multistep processes used in patterning microelectronic structures [4–7]. The result is fewer manufacturing steps, improved yield, higher product throughput, and lower costs. An example is the patterning of a polyimide passivation layer on copper lines to form vias. A patterning process using conventional techniques would involve several steps such as resist application and patterning, a wet or dry etch process for pattern transfer, and stripping of the resist. This patterning process is accomplished with a single laser ablation step. Reference [8] discusses the specific use of the masks described in this paper for patterning polyimide on high-density thin-film packages in IBM. Reference [9] is a review of the many diverse applications of excimer laser processing.

Laser mask development

A typical laser ablation manufacturing tool is very similar in design and construction to an optical lithography tool [10, 11]. Both tools consist of many subsystems such as an illumination source, imaging optics, an *XY* stage, alignment optics, servo control electronics, a central computer, and a mask (**Figure 2**). The major differences between a lithography tool and the ablation tool are the wavelength and intensity of the ultraviolet light. Conventional photoresists in multichip module packaging applications are exposed primarily using 436-nm (G-line) and 365-nm (I-line) light from a mercury arc lamp. With a single exposure 100 ms in duration and using an intensity of 5–10 mJ/cm^2, the peak power density is 0.1 W/cm^2. The primary wavelengths used in manufacturing ablation processing are 248 nm and 308 nm, and the required energy density for the ablation process is of the order of 500 mJ/cm^2. Irradiating the substrate with this large amount of energy is accomplished by using multiple high-energy (150–250 mJ), 20-ns pulses from the excimer laser. This corresponds to a high peak power density in the range of 10^7 W/cm^2, placing new challenges on the optical components of the tool, particularly the mask.

It was recognized early in the development of the laser ablation process that a new mask technology was required[1] [12]. Conventional chromium-coated quartz masks exhibited a damage threshold of 135 mJ/cm^2, and were quickly destroyed under the laser irradiation conditions needed for the ablation of polymers. Other mask structures, such as 0.5-μm-thick aluminum films on quartz and metal foil masks, were examined. These suffered from problems such as low resolution and poor image quality in the case of the foil masks, and a comparable low damage threshold of 150 mJ/cm^2 for the aluminum thin-film masks. In fact, excimer lasers have been used to pattern these same metal thin films using the ablation process [13].

Before commercial use of high-power excimer lasers, mirrors capable of withstanding the output of these lasers were being developed [14, 15]. These mirrors were particularly important for use as reflectors in the laser cavity. The structure with the highest damage threshold and highest reflectivity is a multilayer stack of dielectric films on an optical substrate such as quartz. The stack of dielectric films is an alternating series of a film having a high index of refraction, such as hafnium oxide, and a film having a low index of refraction, such as silicon dioxide. Each layer is one quarter of a wavelength thick. The interface between layers reflects a specific amount of incident light, while the thickness of the layers changes the phase of the reflected light; the overall reflectivity is

[1] J. R. Lankard, J. L. Speidell, and K. Smith, "Masks for Projection Patterning," IBM internal memo, 1988.

determined by the total number of layers. These mirrors have a high damage threshold (≥1.2 J/cm^2) because of the low absorption of the ultraviolet light by the dielectric thin films [13]. These mirrors, capable of withstanding high laser power, were used as a mask substrate for laser ablation masks. The concept and the original fabrication process for these dielectric masks were developed and patented in 1990 by S. Kirch et al. of IBM [16]. The dielectric mask structure is shown in **Figure 3**. The choice of the dielectric coatings, the thickness of each alternating layer, and the number of layers are determined by the ablation parameters and the mask fabrication process. The reflectivity of the mask need only be sufficiently high to reduce the laser fluence in the field area below the laser ablation threshold. Mirrors with reflectivities as low as 90% are routinely used. Reducing the reflectivity reduces the total number of dielectric layers and, thus, the overall thickness requirement. Typically, the total dielectric film thickness on a 90% reflective mask built for use at 308 nm (308-nm mask) is 0.7 μm. In comparison, the dielectric layer is 1.2 μm thick on a 99% reflective, 308-nm mask substrate. Control of the critical dimensions of the pattern is a function of the total dielectric stack thickness. In each of the etching processes, described later, the amount of etching undercut is directly proportional to the dielectric stack thickness. Tighter dimensional control is achieved on thinner dielectric layers.

As described earlier, the laser ablation process has been used to replace conventional processes which used a photolithographic step in combination with wet and/or dry processing steps. This means that all of the critical parameters of the multiple conventional steps must be achieved using the single-step ablation process. This requires that the ablation mask meet the same specifications as the equivalent chrome reticle with regard to image placement, critical dimension control, defects, and, to a lesser extent, mask cost. **Table 1** lists these parameters.

Dielectric mask fabrication

Fabrication of the dielectric masks presents some unique challenges to a mask fabrication facility because of the

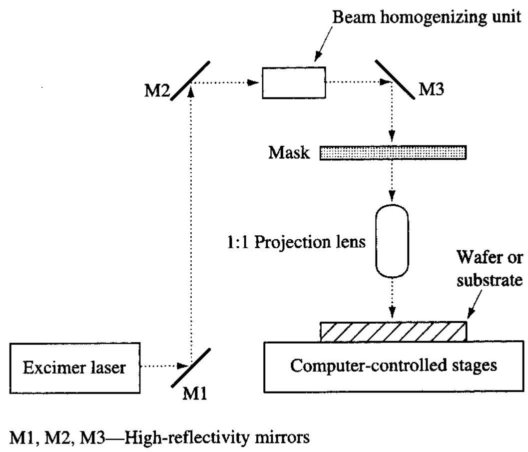

Figure 2

Schematic of the laser ablation tool (all components not shown).

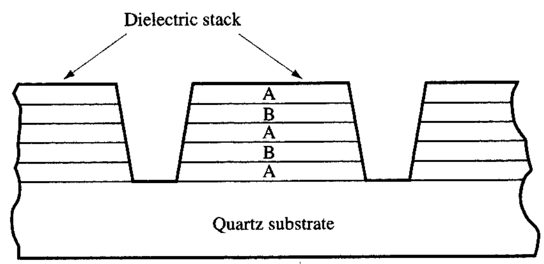

Figure 3

Schematic diagram of the dielectric mask structure. Layer A—high index of refraction, n_1; Layer B—low index of refraction, n_2.

Table 1 Specifications for IBM 1× laser ablation mask.

Wavelength	248 nm	308 nm	308 nm
Mask size, $L \times W \times H$	6 in. × 6 in. × 0.15 in.	6 in. × 6 in. × 0.15 in.	7 in. × 7 in. × 0.15 in.
Field size	40 mm × 100 mm	140 mm × 140 mm	152 mm × 152 mm
Minimum feature size	20 μm	5 μm	5 μm
Feature size tolerance	±1 μm	±0.5 μm	±1.0 μm
Registration accuracy	0.25 μm	0.25 μm	0.35 μm
Defects allowed	<40 μm^2	<20 μm^2	<20 μm^2
Damage threshold	500 mJ/cm^2	800 mJ/cm^2	800 mJ/cm^2

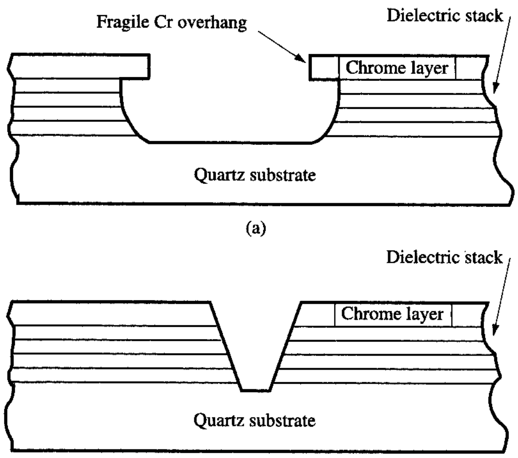

Figure 4

Schematic diagrams of (a) wet-etched mask and (b) ion-beam-etched mask.

properties of the dielectric layers. The dielectric layers on the mask are transparent to visible light and are electrical insulators, which posed problems similar to those now found in the fabrication of certain types of phase-shift masks [17]. The transparency to visible light made inspection for pattern defects and metrology impossible using standard equipment. The lack of electrical conductivity caused charging-related problems when an electron-beam tool was used for resist exposure. Chromium etch processes, both wet and dry, would not etch the dielectric layers. As a result, different processes were used for dielectric mask fabrication. Additional information on the processes used to perform quality control measurements on these masks can be found in Reference [18]. For many applications, the transparency of the dielectric layers to visible light presents the same problem to the end user of the mask as to the mask fabricator. Alignment marks are required to align the patterns on the mask accurately with both the ablation tool and the part to be processed. These alignment marks must be opaque to visible light in order to be useful to standard alignment systems.

The basic fabrication process includes two different etching processes, one wet and one dry, for patterning the dielectric layer. The process is chosen on the basis of specifications for the mask and the dielectric films that have been selected.

The dielectric-coated quartz substrates are provided to the mask fabrication facility as a commodity, as are conventional chrome-on-quartz photomask blanks. The desired dielectric mirror is ordered from an optical coating facility. The substrate type, dielectric films, operating wavelength, reflectivity, and defect density are specified at the time of order. Using either electron-beam evaporation or ion-beam deposition, the alternating layers of dielectric are deposited onto the substrate. The reflectivity of the mirror is monitored *in situ* during the deposition process.

As the patterning process begins, a 0.1-μm-thick layer of chromium is deposited on top of the dielectric films by electron-beam evaporation or magnetron sputtering. The purpose of this film is to eliminate the problems presented by the dielectric layers of transparency to visible light and electrical charging. It also acts as an intermediate pattern layer. The chromium layer allows the use of standard mask-fabrication tools such as electron-beam mask writers, metrology, and inspection tools, of which the latter two use visible light for their operation. A conventional optical or e-beam resist is applied and patterned. The resist pattern is then transferred into the underlying chromium using a suitable wet or dry etching technique. Metrology, critical dimension measurements, defect inspection, and repair are all performed next, treating the mask with patterned chrome as a standard photomask. The pattern is then transferred into the stack of dielectric films.

The wet-etch process is used if the dielectric films are tantalum pentoxide for the high-index-of-refraction film and silicon dioxide for the low-index-of-refraction film, since both of these films are readily etched in the wet etchant. The resist layer is removed and the substrate is wet-etched. The chromium layer acts as the mask and must be defect-free. The etchant [19] is a 55 wt% solution of potassium hydroxide in water at a temperature of 100°C $\pm$ 1°C. An interrupt etch process is used to compensate for differences in the etch rate between the dielectric layers and the quartz substrate. Since the wet-etch process is isotropic, there is a resulting undercut beneath the chromium masking layer, as shown in **Figure 4**. The overhanging chromium must be etched back to the edge of the images in the dielectric layers to produce accurate alignment marks. A layer of optical resist is applied on top of the chromium and is exposed by illuminating the mask from the quartz side, thereby using the patterned chromium as a contact mask. This resist layer is intentionally overexposed, using a vacuum contact printer, to allow the overhanging chromium to be revealed. The chromium is then etched using a suitable wet or dry process. This process has produced patterns as small as 3 μm and exhibits a critical dimension control of $\pm$0.4 μm.

The dry-etch process uses inert gas ion-beam etching to pattern the dielectric layers [20]. In this process, an energetic beam of ions from a Kaufman ion source is directed at the substrate, and through momentum transfer the dielectric atoms are removed. The process is purely physical sputtering, without a chemical reaction at the substrate. The beam of ions is collimated to within 10° about the normal to the mask, which results in anisotropic etching. The resist profile is accurately transferred into the underlying layer. Most materials are etched at approximately the same rate with this process. This requires that the masking layer be thicker than the layer to be patterned in order to ensure an adequate margin for over-etching. The resist layer is typically 1.5 μm for patterning a 0.7-μm-thick dielectric layer. Argon is used as the etching gas, and the ion energy and current density are 400 eV and 0.25 mA/cm^2, respectively. A rotary substrate platform is used to average out nonuniformities of the ion beam to produce uniform etching across the substrate. Ion-beam parameters which result in low power being delivered to the substrate must be used, and the substrate must be cooled during the process to prevent overheating and damaging of the resist layer. Because of the anisotropic nature of this etching technique, the chrome etch-back step required for the wet-etch process is unnecessary (Figure 4). This process has produced patterns as small as 2 μm and exhibits a critical dimension control of $\pm$0.5 μm.

The wet-etch process is currently used at IBM for the patterning of dielectric masks. This process works well with a limited set of dielectric films, and has produced a lower defect density than the dry-etch process. The dry-etch process is more versatile, since all dielectric films can be etched using this technique. The dry-etch process has demonstrated better resolution but a higher defect density, since it is more sensitive to particulate contamination.

At this point, both fabrication processes merge onto a single path for mask completion. The critical alignment marks are transferred into the chromium and dielectric layers along with the device pattern. Next, the chromium is selectively removed from the device pattern and left in the alignment mark region using an optical lithography step and wet etching of the chromium. Metrology of the pattern in the dielectric stack on the mask is next performed using a Leitz metrology system model LMS 2000 or equivalent tool [18].

Defects and repair processes

The most common mechanism for printable defects is holes that penetrate completely through the dielectric stack. The laser ablation process is insensitive to holes that penetrate less than two thirds of the way through the stack because not enough laser light passes through the hole to exceed the ablation threshold of the material. The current fabrication process produces masks with a defect density of 0.0003/cm^2 for a defect size of 20 μm^2 or greater, a density comparable to those of conventional chrome-on-quartz photomasks. Although our current ablation processes do not require lower defect specification at this time, the mask process has demonstrated the ability to achieve a defect specification of 0.0003/cm^2 for a defect size of 4 μm or greater. There are several sources of both clear and opaque defects in the final mask. Defects (either pinholes or inclusions) in the dielectric stack result in defects in the final mask. Defects in the resist layer are transferred into the chromium and dielectric layers. In the wet-etch process, the patterned chrome layer is inspected and repaired, since it acts as the etching mask for the dielectric layers. Repaired clear defects in the chrome layer must seal against the wet etchant to prevent the defect from transferring into the dielectric layer. It has been found that microscopic silicon carbide particles can become embedded in the surface of the quartz substrate during the polishing operation. Because of the high intrinsic stress in this region, a circular fracture can be generated in the dielectric layer and in the quartz substrate, often resulting in the loss of the dielectric stack and the creation of a clear defect. Organic contamination ("soft" defects) is less of a problem in laser ablation masks than on photomasks. Due to the high fluence of the ultraviolet light, most organic contaminants are ablated from the surface of masks. For this reason, pellicles are not required in the use of dielectric masks.

Mask-repair technologies have been developed to repair both clear and opaque defects in these masks. Clear defects are repaired using a proprietary laser process which results in a concave feature being produced at the defect site. This concave feature acts as a lens to lower the intensity of light which passes through the defect below the ablation threshold for the material. Opaque defects in the mask can be repaired by applying a resist layer, patterning the resist to reveal the defect, and ion-beam etching to remove the material.

Summary

Dielectric masks have been used in IBM manufacturing since 1987 for the laser ablation patterning of polyimide layers. These polyimide layers are used in the fabrication of high-density multilevel thin-film packages for multichip modules. The ablation process is performed using 308-nm light with a fluence of 200–250 mJ/cm^2 and a pulse repetition rate of 300 Hz. The ablation process has never destroyed a mask, and the masks receive periodic mechanical scrub cleaning to remove large particulates. These masks have demonstrated an acceptable damage threshold and lifetimes of more than five years. A manufacturing process has been developed with yields in excess of 90%. To date, more than 1000 masks have been produced which meet process specifications. The fabrication process, either wet- or dry-etch, can produce images as small as 3 μm with a critical dimension control of ± 0.5 μm. Layer-to-layer registration on these masks achieves the same precision as on conventional photomasks, limited only by the pattern generator. Commercial sources of dielectric mask blanks such as Balzers[2] have been established, making these blanks a commodity similar to chromium-on-quartz mask blanks. (Table 1 presents the various standard mask configurations which are routinely produced, and their specifications.) These masks have proven to be robust and durable in a manufacturing environment.

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