

Laser machining using an active assist gas

This invention relates to laser machining using an active assist gas.

It is known that etching of a silicon wafer substrate in an SF₆ environment results in clean and smooth etching of the silicon substrate.

5 Also, the presence of SF₆ during laser machining improves both the quality and efficiency of the material removal process. However, although, the presence of this gas assists the material removal, typically this does not allow laser machining at a rate to enable sufficiently high throughput machining for manufacturing.

10 US 3679502 describes a method for non-localised etching of silicon wafer substrates heated to a temperature in a region of 950 to 1250 °C in an SF₆ environment. Fluorine radicals produced at such elevated temperatures etch the silicon surface resulting in a smooth clean surface.

15 In US 3866398 a reagent gas such as SF₆ is disclosed as being introduced locally to a machining region during a laser scribing process. The reagent gas reacts with high temperature vapour ejected from a substrate material during laser machining to produce gaseous compounds that do not redeposit as solid debris on the substrate to be machined.

20 US 4331504 discloses the utilisation of a CO₂ laser vibrationally to excite SF₆ molecules for directional non-localised etching of a masked wafer substrate. The CO₂ laser energy is sufficiently low so as to prevent direct laser ablation of the wafer substrate.

25 US 4617086 describes a method for fast local etching of a silicon substrate in an SF₆ environment using a continuous laser at a wavelength of 0.6 microns or less to photo-dissociate the SF₆ molecule. The laser power density is in the region of 6×10^5 W/cm² and is below an ablation threshold of silicon and so etching is primarily preformed by the interaction between the silicon substrate and fluorine radicals produced when the laser is on.

US 4731158 discloses a mixture of H_2 and a fluorine-containing molecule such as NF_3 , SF_6 and COF_2 used in order to improve a speed of laser photo-dissociative etching of silicon relative to performing a same etching process in an environment of just fluorine-containing molecules. Etching of the substrate material is performed by fluorine radicals produced as a result of the photo-dissociation process.

It is an object of the present invention at least to mitigate the aforesaid deficiencies in the prior art.

It is a particular object of an embodiment of the present invention to utilise the advantages of laser machining in an SF_6 environment for a laser dicing process that results in low debris laser machining and/or superior strength of diced substrate parts. This superior die strength arises from the high quality machining achievable using an SF_6 assist gas during the laser machining process.

According to a first aspect of the present invention there is provided a method of laser machining a silicon workpiece comprising the steps of: providing a halogen environment for the silicon workpiece to form an active assist gas for the laser machining; providing a laser beam with a wavelength of less than 0.55 microns; and focusing the laser beam onto the silicon workpiece at a power density above an ablation threshold of silicon in order to laser machine the workpiece in the presence of the assist gas so that the assist gas reacts with the silicon workpiece at or near a focus of the laser beam such that laser machining speed is increased and strength of the machined workpiece is increased due to an improvement in machining quality.

Conveniently, the step of providing a halogen environment comprises the steps of providing a sulphur hexafluoride (SF_6) environment and dissociating at least some of the sulphur hexafluoride with the laser beam to form fluorine radicals as the active assist gas.

Advantageously, the method is for dicing a silicon wafer, such that use of the assist gas increases strength of resultant dies.

Preferably, the step of providing a halogen environment comprises providing a fluorine environment as the active assist gas and the step of reacting the active assist gas with the silicon workpiece comprises reacting the fluorine with the silicon workpiece to form gaseous silicon tetrafluoride (SiF₄).

- 5 Conveniently, the step of laser machining the workpiece comprises at least one of wafer dicing, via drilling and surface patterning.

Preferably, the method includes an additional step of providing gas extraction means for removing at least one of gas-borne debris and waste gas from the environment of the workpiece.

- 10 Advantageously, the method includes a further step, after the step of laser machining the workpiece, of cleaning the workpiece of residues generated by the laser machining.

Conveniently, the step of cleaning the workpiece comprises the step of dry wiping the workpiece.

- 15 Alternatively, or in addition, the step of cleaning the workpiece comprises a water spin-rinse-dry process.

Alternatively, or in addition, the step of cleaning the workpiece comprises the step of laser cleaning the workpiece.

- 20 Advantageously, the step of laser cleaning the workpiece comprises scanning the workpiece with a defocused or low energy laser beam.

Conveniently, the step of laser cleaning the workpiece comprises laser cleaning the workpiece in an air environment.

Preferably, the step of laser cleansing the workpiece comprises laser cleaning the workpiece in an active assist gas environment.

- 25 Preferably, the active assist gas is fluorine or fluorine-based.

Conveniently, fluorine radicals are produced by laser photo-dissociation of sulphur hexafluoride at the workpiece.

Conveniently, where the workpiece is a silicon substrate with active devices on a first major face thereof, the step of providing a halogen environment for the workpiece comprises an initial step of mounting the substrate with the first major face on tape frame means and the step of machining the workpiece comprises
5 machining the substrate from a second major face opposed to the first major face.

According to a second aspect of the invention, there is provided a laser machining apparatus for machining a silicon workpiece comprising: assist gas delivery means for providing a halogen environment for the silicon workpiece; laser source means for producing a laser beam with a wavelength of less than 0.55
10 microns; and laser beam delivery means for focusing the laser beam at a power density above an ablation rate of silicon, onto the silicon workpiece such that the laser beam machines the silicon workpiece at the focus of the laser beam and the assist gas reacts with the silicon workpiece at or near the focus of the laser beam to increase laser machining speed and to provide an improvement in machining
15 quality such that strength of the machined workpiece is increased.

Preferably, the apparatus further comprises gas extraction means for extracting at least one of gas-borne debris and waste gas from the environment of the workpiece.

Conveniently, the assist gas delivery means comprises means for delivering
20 sulphur hexafluoride.

Conveniently, the apparatus is arranged for dicing a silicon wafer such that use of the assist gas increases strength of resultant dies.

Advantageously, the laser source means comprises a diode-pumped laser operating at a second, third or fourth harmonic at a wavelength of less than 0.55
25 microns.

Conveniently, the laser beam delivery means comprises a galvanometer with a scan lens and an XY motion stage for positioning the workpiece in relation to the laser beam.

Advantageously, the apparatus further comprises tape frame means for mounting the workpiece for machining the workpiece from a second major face of the workpiece opposed to a first face of the workpiece having active devices thereon.

5 The invention will now be described, by way of example, with reference to the accompanying drawings in which:

Figure 1 is a graph of machining speed as ordinates vs. wafer thickness as abscissa for laser machining according to the invention and according to the prior art;

10 Figure 2 is a graph of survival probability (%PS) as ordinates vs. die strength (N/mm^2) as abscissa for patterned wafers using laser machining according to the invention and according to the prior art and using saw street cutting techniques;

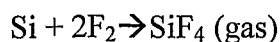
Figure 3 shows plots of average, maximum and minimum die strength
15 values for laser and saw cut silicon die;

Figure 4 is a schematic diagram of a laser machining apparatus according to the present invention.

In the Figures like reference numerals denote like parts.

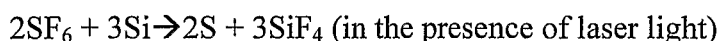
The present invention relates particularly to laser dicing of a silicon substrate
20 at a laser power density above the silicon ablation threshold in an SF_6 environment. Silicon material is primarily removed from the wafer substrate by the laser ablation process. The addition of SF_6 results in an increase in laser dicing speed and also an increase in die strength of laser machined die due to an improvement in machining quality. This improvement may be compared with
25 improved etching with SF_6 in the prior art, namely, the surface of features laser machined in an SF_6 environment is smoother than that obtained with laser machining in air. However, in the present invention, etching of the silicon is substantially confined to a localised region of the workpiece on which the laser is focused. Also, material ejected during the laser ablation process reacts with the
30 SF_6 environment and can be removed from a machining site in a gaseous form rather than being re-deposited as solid debris around the laser machining site.

Silicon reacts vigorously with all halogens to form silicon tetrahalides. It reacts with fluorine (F₂), chlorine (Cl₂), bromine (Br₂) and iodine (I₂) to form respectively silicon tetrafluoride (SiF₄), silicon tetrachloride (SiCl₄), silicon tetrabromide (SiBr₄), and silicon tetra-iodide (SiI₄). The reaction with fluorine
5 takes place at room temperature but the others require heating to over 300°C.



Reaction 1

It is known that molten silicon reacts with sulphur hexafluoride (SF₆) according to the following reaction:



Reaction 2

As the reaction of SF₆ and silicon is not spontaneous, occurring only at energies above the melting threshold of silicon, it may be very localized and thus
10 suitable for one-step silicon micro-machining applications such as wafer dicing, via drilling and surface patterning.

Referring to figure 4, a laser dicing system 1 of the present invention includes a diode-pumped laser 2 operating in the second, third, or fourth harmonic, at a wavelength of less than 0.55 microns, and a beam delivery system
15 3 that delivers the laser beam to the surface of a silicon wafer 5. Wavelengths in the regions of 366nm or 355nm are suitable. The silicon wafer may be blank or may have different layers patterned on it. The beam delivery system includes a galvanometer with a scan lens to direct the beam within an available field of view while an XY motion stage 6 is used to position the silicon wafer 5 to be machined.
20 The system includes a gas delivery system 7 and an extraction system 8 that delivers SF₆ gas to the wafer surface and captures airborne debris and waste gas subsequent to laser machining, respectively. The laser beam may be directed to the desired machining site on the wafer 5 through a laser window 9 in an enclosure for enclosing an active assist gas around the wafer 5. To machine the
25 wafer, the laser beam 4 heats the silicon wafer 5 such that its temperature is sufficient for Reaction 2 to take place. Fluorine radicals dissociated from SF₆ by

the laser then etch the silicon in Reaction 1 by bonding with the silicon to form gaseous silicon tetrafluoride (SiF_4). Due to the reaction with the SF_6 gas, the silicon machining rate is significantly faster than that achieved when an active assist gas is not used.

5 An example of the advantage in the machining speed gained when SF_6 is used as an assist gas during laser machining is shown in Figure 1, in which plot 11 is for laser machining in air and plot 12 is for laser machining in a SF_6 environment. As can be seen, the machining speed for a wafer substrate is faster in a SF_6 environment for all thicknesses of wafer studied and for wafers less than
10 250 microns thick is more than three times faster in an SF_6 environment than in air.

 The die strength, as measured using a known Weibull die strength test, of components which are diced using SF_6 as an active assist gas during laser machining is higher than that achieved when an assist gas is not used. That is, it is
15 found that there is a significant increase in the strength of silicon die tested subsequent to laser machining using SF_6 as an assist gas. Figure 2 shows plots, for saw-cut die 21, laser machined die using an air environment 22 and laser machined die using a SF_6 environment 23, of the probability of survival vs. the pressure applied to break the die. It can be seen that the die strength for laser
20 machined die in an air environment, plot 22, is less than the strength of traditional saw-cut die, plot 21, whereas the strength of die laser machined in a SF_6 environment, plot 23, is greater than that of saw-cut die, plot 21. In fact, it is found that using a beam overlap of 70%, the die strength of laser-machined components is up to 4.8 times stronger than that of components machined without
25 the use of gas assist. Moreover, it was also found that die cut in SF_6 gas were 1.65 times stronger than die cut using a saw cutting technique.

 Referring to Figure 3, laser machining with SF_6 as an active assist gas resulted in average die strength value 31 in excess of 300MPa compared to a value
32 of 185MPa for a conventional saw cutting technique and a value 33 of 65MPa
30 for laser machining in the absence of an assist gas.

When silicon is machined with SF₆ as an assist gas, the majority of the by-products are in gaseous form and are vented away, but some solid debris remains and may be re-deposited on the wafer. This debris can be easily removed with a dry wipe process.

5 If for any reason the application of the dry wipe method is not applicable or desirable, removal of this solid debris is possible by defocusing the laser beam and scanning the contaminated area at a higher speed than used for machining, freeing debris from the surface and permitting it to be captured by the extraction system 8. It may be necessary to scan the same area of the workpiece or substrate more than
10 once in order to perform satisfactory cleaning, however, during cleaning the power of the laser beam is sufficiently low to prevent damage to the silicon or any other layer on the wafer. It is not necessary to use an assist gas for this cleaning, but the efficiency of the process is increased if SF₆ is used.

15 It is possible that the top layers of the wafer may be photosensitive, so that it is not practical to use a scanning laser beam on the top surface of the wafer. In this case it is possible to process the wafer from a backside of the wafer.

Specifically, using a vision system to align a wafer for machining from a bottom of the wafer, the wafer may be mounted face downward on a tape. Typically, the tape is transparent to visible radiation. With a vision system in
20 registration with the laser system, the laser beam can be delivered to a back surface of the wafer. This ensures all debris generated is on the back of the wafer.

Once diced in this manner the wafer may be laser cleaned (dry) or washed, without components on the front of the wafer being contacted by water.

25 In a further embodiment of the invention the wafer is enclosed in a closed chamber. Gas flow into and out of the chamber is regulated to ensure efficient machining and control of gas usage. A valve system may also be used to ensure gas flow into the chamber is controlled so that sufficient gas is delivered during the laser "ON" period.

Finally, apparatus to remove and recirculate gas not consumed in the reaction may include facilities for extraction and filtering of reaction by-products and for returning un-reacted gas to the reaction area.

Although the invention has been described using fluorine derived from SF₆,
5 to machine silicon, it will be understood that other halogens and other sources of halogens may be used, for example, CF₄. Moreover, it will be understood that the invention has application to machining other semiconductor materials with appropriate assist gases which enhance machining.

The invention provides the advantages, in the use of UV lasers, operating
10 particularly in the range of 366nm or 355nm, for dicing and machining silicon, and other semiconductors, with high pulse repetition frequency and using multiple passes, as described, for example, in WO 02/34455, where the assist gas is used to enhance the dicing or machining process such that the speed of the process is improved, the nature of the debris is modified to enable more efficient cleaning
15 and where the process itself, using the assist gas, provides die with higher die strength than that achievable without the use of assist gas.

Typical examples of where the invention provides a major advantage are in the manufacture of, for example, smart cards, stacked integrated circuits and integrated circuits. For integrated circuits, die strength is critical to short and long
20 term reliability of the diced component.

CLAIMS

1. A method of laser machining a silicon workpiece (5) comprising the steps of:
 - a. providing a halogen environment for the silicon workpiece to form an active assist gas for the laser machining;
 - b. providing a laser beam (4) with a wavelength of less than 0.55 microns; and
 - c. focusing the laser beam onto the silicon workpiece at a power density above an ablation threshold of silicon in order to laser machine the silicon workpiece in the presence of the assist gas so that the assist gas reacts with the silicon workpiece at or near a focus of the laser beam such that laser machining speed is increased and strength of the machined workpiece is increased due to an improvement in machining quality.
2. A method as claimed in claim 1, wherein the step of providing a halogen environment comprises the steps of providing a sulphur hexafluoride (SF_6) environment and dissociating at least some of the sulphur hexafluoride with the laser beam to form fluorine radicals as the active assist gas.
3. A method as claimed in claim 2, for dicing a silicon wafer, such that use of the assist gas increases strength of resultant dies.
4. A method as claimed in any of claims 1 to 3, wherein the step of providing a halogen environment comprises providing a fluorine environment as the active assist gas and the step of reacting the active assist gas with the silicon workpiece comprises reacting the fluorine with the silicon workpiece to form gaseous silicon tetrafluoride (SiF_4).
5. A method as claimed in any of the preceding claims, wherein the step of laser machining the workpiece comprises at least one of wafer dicing, via drilling and surface patterning.

6. A method as claimed in any of the preceding claims, including an additional step of providing gas extraction means for removing at least one of gas-borne debris and waste gas from the environment of the workpiece.
7. A method as claimed in any of the preceding claims, including a further step, after the step of laser machining the workpiece, of cleaning the workpiece of residues generated by the laser machining.
8. A method as claimed in claim 7, wherein the step of cleaning the workpiece comprises the step of dry wiping the workpiece.
9. A method as claimed in claims 7 or 8, wherein the step of cleaning the workpiece comprises a water spin-rinse-dry process.
10. A method as claimed in any of claims 7 to 9, wherein the step of cleaning the workpiece comprises the step of laser cleaning the workpiece.
11. A method as claimed in claim 10, wherein the step of laser cleaning the workpiece comprises scanning the workpiece with a defocused or low energy laser beam.
12. A method as claimed in claims 10 or 11, wherein the step of laser cleaning the workpiece comprises laser cleaning the workpiece in an air environment.
13. A method as claimed in any of claims 10 or 11, wherein the step of laser cleaning the workpiece comprises laser cleaning the workpiece in an active assist gas environment.
14. A method as claimed in claim 13, wherein the active assist gas is fluorine or fluorine-based.
15. A method as claimed in any of the preceding claims, wherein fluorine radicals are produced by laser photo-dissociation of sulphur hexafluoride at the silicon workpiece.
16. A method as claimed in any of the preceding claims, wherein where the workpiece is a silicon substrate with active devices on a first major face thereof, the step of providing a halogen environment for the workpiece

comprises an initial step of mounting the substrate with the first major face on tape frame means and the step of machining the workpiece comprises machining the substrate from a second major face opposed to the first major face.

- 5 17. A laser machining apparatus (1) for machining a silicon workpiece (5) comprising: assist gas delivery means (7) for providing a halogen environment for the silicon workpiece; laser source means (2) for producing a laser beam (4) with a wavelength of less than 0.55 microns; and laser beam delivery means (3, 6) for focusing the laser beam at a power density
10 above an ablation rate of silicon, onto the silicon workpiece such that the laser beam machines the silicon workpiece at the focus of the laser beam and the assist gas reacts with the silicon workpiece at or near the focus of the laser beam to increase laser machining speed and to provide an improvement in machining quality such that strength of the machined
15 workpiece is increased.
18. An apparatus as claimed in claim 17, wherein the apparatus further comprises gas extraction means (8) for extracting at least one of gas-borne debris and waste gas from the environment of the workpiece.
19. An apparatus as claimed in claims 17 or 18, wherein the assist gas delivery
20 means (7) comprises means for delivering sulphur hexafluoride.
20. An apparatus as claimed in claim 19, arranged for dicing a silicon wafer such that use of the assist gas increases strength of resultant dies.
21. An apparatus as claimed in any of claims 17 to 20, wherein the laser source means (2) comprises a diode-pumped laser operating at a second, third or
25 fourth harmonic at a wavelength of less than 0.55 microns.
22. An apparatus as claimed in any of claims 17 to 21, wherein the laser beam delivery means comprises a galvanometer with a scan lens and an XY motion stage (6) for positioning the workpiece (5) in relation to the laser beam (4).

23. An apparatus as claimed in any of claims 17 to 22, wherein the apparatus further comprises tape frame means for mounting the workpiece for machining the workpiece from a second major face of the workpiece opposed to a first face of the workpiece having active devices thereon.