A novel and unique technique to create nanometer to micrometer scale orifices in and through transparent material such as Si wafers, glass or Sapphire is disclosed. It has many of the advantages mentioned heretofore and many novel features that result in a new method of producing non-abatively drilled orifices in materials which is not anticipated, rendered obvious, suggested, or even implied by any of the prior art, either alone or in any combination thereof. Specifically, it offers the following huge advances over the prior art: smoother orifice sides, minimal microcrack propagation, longer/deeper orifice creation, non tapered orifices, nonlinear absorption, orifices with a consistent internal diameter, minimized entrance distortion and reduced collateral damage.

The subject matter of the present invention is particularly pointed out and distinctly claimed in the concluding portion of this specification. However, both the organization and method of operation, together with further advantages and objects thereof, may best be understood by reference to the following description taken in connection with accompanying drawings wherein like reference characters refer to like elements. Other objects, features and aspects of the present invention are discussed in greater detail below.

Brief Description of the Drawings

FIG 1 is a diagrammatic representation of a prior art abative laser drilling arrangement wherein the principle focus occurs at the top surface of the transparent substrate;

FIG 2 is a perspective view of an orifice formed by the drilling arrangement of FIG 1;

FIG 3 is a representative side view of a prior art ablative laser drilling arrangement wherein the principle focus occurs below the top surface of the transparent substrate;

FIG 4 is a perspective view of a an orifice formed by the drilling arrangement of FIG 3;

FIG 5 is a representative side view of an orifice ablatively drilled as the laser arrangement of FIG 1 wherein the primary focus occurs at the top surface of the transparent substrate;

FIG 6 is a diagrammatic representation of the laser drilling arrangement of the present invention wherein the primary focus occurs above the top surface of the transparent substrate;

FIG 7 is a perspective view of an orifice scribe in a transparent substrate formed by the laser drilling arrangement of the present invention;

FIG 8 is a representative side view of two orifices drilled by the laser arrangement of FIG 6;

FIG 9 is a diagrammatic representation of the prior art ablative laser drilling arrangement;

FIG 10 is a diagrammatic representation of the present invention;

FIG 11 is a diagrammatic view of the present invention utilizing a distributed focus lens arrangement;

FIG 12 is a diagrammatic view of the present invention utilizing a distributed focus lens arrangement;

FIG 13 is a diagrammatic view of the present invention utilizing a distributed focus lens arrangement and the distribution of focal waists where the principal focus is above the target;

FIG 14 is a is a diagrammatic view of the present invention utilizing a distributed focus lens arrangement and the distribution of focal waists where the principal focus is below the target;

drilled, cause a rough orifice wall and result in an orifice with a taper 22 having a different diameter at the top and bottom surfaces of the target 10. (FIG 5) This occurs because in ablative machining, the beam has central focus 8 (also referred to as a principle focal waist) at the surface of the target 10 causing localized heating and thermal expansion therein heating the surface of the material 10 to its boiling point and generating a keyhole. The keyhole leads to a sudden increase in optical absorptivity quickly deepening the orifice. As the orifice deepens and the material boils, vapor generated erodes the molten walls blowing ejecta 20 out and further enlarging the orifice 22. As this occurs, the ablated material applies a pulse of high pressure to the surface underneath it as it expands. The effect is similar to hitting the surface with a hammer and brittle materials are easily cracked. (Additionally, brittle materials are particularly sensitive to thermal fracture which is a feature exploited in thermal stress cracking but not desired in orifice drilling.) OB generally is reached when the debris is not ejected, a bubble is created in the orifice 22 or there is a violent ablation that cracks the target in the area of the orifice 22. Any one or combination of these effects causes the beam 2 to scatter from this point or be fully absorbed not leaving enough beam power (fluence) to drill down through the material 10 any further. Additionally, this creates a distortion or roughness known as the ablative ejecta mound 20 found around the initiating point at the surface of the target substrate 10. (FIG 5)

Another problem with laser ablation techniques is that the orifices it drills are not of a uniform diameter as the laser beam filamentation changes its diameter as a function of distance. This is described as the Rayleigh range and is the distance along the

falling burst envelope profiles of FIG 19 represent a particularly useful means of process control especially well adapted for removing thin metal layers from dialectric materials.

Looking at FIGS 13-16 collectively, the mechanism of the present invention can best be illustrated. Herein, burst picosecond pulsed light is used because the total amount of energy deposited in the target material is low and photoacoustic compression can proceed without cracking the material, and less heat is generated in the target material thus efficient smaller packets of energy are deposited in the material so that the material can be raised incrementally from the ground state to a maximally excited state without compromising the integrity of the material in the vicinity of the filament.

The actual physical process occurs as described herein. The principal focal waist of the incident light beam of the pulsed burst laser is delivered via a distributed focusing element assembly to a point in space above or below (but never within) the target material in which the filament is to be created. This will create on the target surface a spot as well as white light generation. The spot diameter on the target surface will exceed the filament diameter and the desired feature (orifice, slot, etc.) diameter. The amount of energy thus incident in the spot on surface being greater than the critical energy for producing the quadratic electo-optic effect (Kerr effect - where the change in the refractive index of the material is proportional to the applied electric field) but is lower than the critical energy required to induce ablative processes and more explicitly below the optical breakdown threshold of the material. Self-focusing occurs above a critical power that satisfies the relationship whereby the power is inverse to the product of the real and complex indices of refraction for the target material. Photacoustic compression proceeds as a consequence of maintaining the required power in the target

CLAIMS

1. A photoacoustic compression method for machining a transparent target material, comprising the steps of:

providing a laser beam having at least one burst of laser pulses, a wavelength of less than 5 μm, a burst repetition rate between 1 Hz to 2 MHz, a number of subpulses in the range of 2 to 50 per burst, and, each pulse having a pulse energy of 0.5-1000 μJ;

passing said laser beam from a laser beam source through a distributive focus lens focusing assembly, thereby focusing said laser beam;

applying said focused laser beam to a surface of said transparent target, a total pulse energy or fluence applied to said transparent target at a spot where said laser beam contacts said surface of said transparent target being sufficient to cause Kerr effect self focusing and thereby form a filament, said spot being the point of initiation of machining on said transparent target determined by said wavelength, said burst repetition rate, said number of subpulses per burst, and said pulse energy; and,

adjusting said wavelength, adjusting said burst repetition rate, adjusting said number of subpulses per burst, and adjusting said energy per pulse to propagate said filament and annularly compress said target material about said filament while minimizing ablative ejecta.

2. The photoacoustic compression method for machining a transparent target material, as claimed in claim 1, wherein said focusing comprises:

delivering said laser pulses to said surface of said transparent target after adjustment of the relative distance or angle of said distributive focus lens focusing assembly in relation to said laser source;

focusing said laser beam in said distributive focus lens focusing assembly so as to create a principal focal waist and at least one secondary focal waist; and,

adjusting said principal focal waist such that said principal focal waist does not reside on or in said transparent target that is being machined.

3. The photoacoustic compression method for machining a transparent target material, as claimed in claim 1, wherein said focusing comprises:

delivering said laser beam to said surface of said transparent target after adjustment of the relative distance or angle of said distributive focus lens focusing assembly in relation to said laser source; and,

focusing said laser beam in said distributive focus lens focusing assembly so as to create a principal focal waist and at least one secondary focal waist; and,

adjusting said transparent target distance with respect to said principal focal waist and at least one secondary focal waist.

4. The photoacoustic compression method for machining a transparent target material, as claimed in claim 2, further comprising the steps of:

adjusting said focus of said laser beam such that said spot is located below or above said principal focal waist, said spot has a diameter larger than a diameter of said filament formed in said transparent target.

5. The photoacoustic compression method for machining a transparent target material, as claimed in claim 3, further comprising the steps of:

adjusting said focus of said laser beam such that said spot is located below or above said principal focal waist, said spot has a diameter larger than a diameter of said filament formed in said transparent target.

6. The photoacoustic compression method for machining a transparent target material, as claimed in claim 2, wherein said transparent target may be comprised of one or a set of transparent wafers, plates or substrates in a layered configuration; and wherein machining of said transparent target is the drilling of stopped or through orifices beginning at any depth and in any one of said set of wafers, plates or substrates in said layered configuration.

7. The photoacoustic compression method for machining a transparent target material, as claimed in claim 3, wherein said transparent target may be comprised of one or a set of transparent wafers, plates or substrates in a layered configuration; and wherein machining of said transparent target is the drilling of stopped or through orifices beginning at any depth and in any one of said set of wafers, plates or substrates in said layered configuration.

8. The photoacoustic compression method for machining a transparent target material, as claimed in claim 1, wherein said transparent target may be comprised of one or a set of transparent wafers, plates or substrates in a layered configuration; and wherein machining of said transparent target is the drilling of stopped or through orifices beginning at any depth and in any one of said set of wafers, plates or substrates in said layered configuration.

9. The photoacoustic compression method for machining a transparent target material, as claimed in claim 2, wherein said distributive focus lens focusing assembly determines said fluence level of said at least one secondary focal waist, said at least one secondary focal waist having sufficient intensity and number to ensure propagation of said filament through a desired volume of said transparent target.

10. The photoacoustic compression method for machining a transparent target material, as claimed in claim 3, wherein said distributive focus lens focusing assembly determines said fluence level of said at least one secondary focal waist, said at least one secondary focal waist having sufficient intensity and number to ensure propagation of said filament through a desired volume of said transparent target.

11. The photoacoustic compression method for machining a transparent target material, as claimed in claim 1, wherein said laser pulses have a spacing sufficient to maintain photoacoustic compression within said transparent target, said laser pulses having a pulse width of less than 10 nanoseconds.

12. The photoacoustic compression method for machining a transparent target material, as claimed in claim 1, including applying a sacrificial layer to said surface of said material prior to the said application of said laser beam.

13. The photoacoustic compression method for machining a transparent target material, as claimed in claim 1, wherein no material is removed from said transparent target by said photoacoustic compression.

14. The photoacoustic compression method for machining a transparent target material, as claimed in claim 1, wherein said distributive focus lens focusing assembly is selected from the group consisting of: aspheric plates, telecentric lenses, non-telecentric lenses, aspheric lenses, axicon, annularly faceted lenses, custom ground aberrated non-perfect lenses, a combination of positive and negative lenses or a series of corrective plates, and, an optical element tilted with respect to the incident beam.

15. A photoacoustic compression method for machining a transparent target material, comprising the steps of:

providing a laser beam having at least one burst of laser pulses, a wavelength of less than 5 μm, a burst repetition rate between 1 Hz to 2 MHz , a number of subpulses in the range of 2 to 50 per burst, said subpulses have a spacing sufficient to maintain photoacoustic compression, said laser pulses having a pulse width of less than 10 nanoseconds and having a pulse energy of 0.5-1000 μJ;

passing said laser beam from a laser source through a distributive lens focusing assembly;

delivering said laser beam to said transparent target after adjustment of the relative distance or angle of said distributive focus lens focusing assembly in relation to said laser source so as to focus said laser beam in a distributed focus configuration creating a principal focal waist and at least one secondary focal waist;

whereby photoacoustic compression machining is produced by said laser pulse energy delivered to said transparent target, which initiates a Kerr Effect self focusing, thereby producing a filament that is propagated in said transparent target by additional energy input by said at least one secondary focal waist; and,

whereby total energy input to said transparent target is below the level required to initiate ablative or vaporization based machining of said transparent target.

16. The photoacoustic compression method for machining a transparent target material, as claimed in claim 15, wherein no material is removed from said transparent target by said photoacoustic compression.

17. The photoacoustic compression method for machining a transparent target material, as claimed in claim 15, wherein said distributive focus lens focusing assembly is selected from the group consisting of: aspheric plates, telecentric lenses, non-telecentric lenses, aspheric lenses, axicon, annularly faceted lenses, custom ground aberrated non-perfect lenses, a combination of positive and negative lenses or a series of corrective plates, and, an optical element tilted with respect to the incident beam.

18. A photoacoustic compression method for machining a transparent target material, comprising the steps of:

applying a laser beam having at least one burst of laser pulses, said burst having a number of subpulses in the range of 2 to 50;

passing said laser beam from a laser source through a distributive focusing assembly and to said transparent target;

adjusting said distributive focusing assembly position in relation to said laser source and said transparent target; and

creating a principal focal waist and at least one secondary focal waist;

whereby photoacoustic compression machining is produced by said laser beam delivered to said transparent target, which initiates a Kerr Effect self focusing, thereby producing a filament that is propagated in said transparent target by additional energy input by said at least one secondary focal waist.

19. The photoacoustic compression method for machining a transparent target material, as claimed in claim 18, wherein no material is removed from said transparent target by said photoacoustic compression.

20. The photoacoustic compression method for machining a transparent target material, as claimed in claim 18, wherein said distributive focusing assembly is selected from the group consisting of: aspheric plates, telecentric lenses, non-telecentric lenses, aspheric lenses, axicon, annularly faceted lenses, custom ground aberrated non-perfect lenses, a combination of positive and negative lenses or a series of corrective plates, and, an optical element tilted with respect to the incident beam.

21. The photoacoustic compression method for machining a transparent target material, as claimed in claim 18, further comprising the step of: creating a plurality of secondary focal waists within said transparent target.

22. The photoacoustic compression method for machining a transparent target material, as claimed in claim 2, further comprising the step of:

creating a plurality of secondary focal waists within said transparent target.

23. The photoacoustic compression method for machining a transparent target material, as claimed in claim 1, further comprising the step of:

creating a principal focal waist above or below said transparent target; and,

creating a plurality of secondary focal waists within said transparent target.

24. The photoacoustic compression method for machining a transparent target material, as claimed in claim 1, wherein said transparent target material is selected from the group consisting of glass, oxide glasses, borosilicate glass, chemically or heat strengthened glass, glass ceramics, Sapphire, glass layered on Sapphire, glass coated with metals, glass coated with polymers, SiC, GaN, and Si wafers.