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(54) **WAFER MEASUREMENT SYSTEM AND APPARATUS**

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(57) **ABSTRACT**

A method and apparatus for the measurement of wafer thickness, flatness and the trench depth of any trenches etched thereon using the back surface of the wafer to accurately measure the back side of a trench, rendering the trench an effective bump, capable of being measured on the top surface and the bottom surface through a non-contact optical instrument that simultaneously measures the wavelength of the top surface and bottom surface of the wafer, converting the distance between wavelengths to a thickness measurement, using a light source that renders the material of which the wafer is composed transparent in that wavelength range, i.e., using the near infrared region for measuring the thickness and trench depth measurement of wafers made of silicon, which is opaque in the visible region and transparent in the near infrared region. Thickness and flatness, as well as localized shape, can also be measured using a calibration method that utilizes a pair of optical styli.

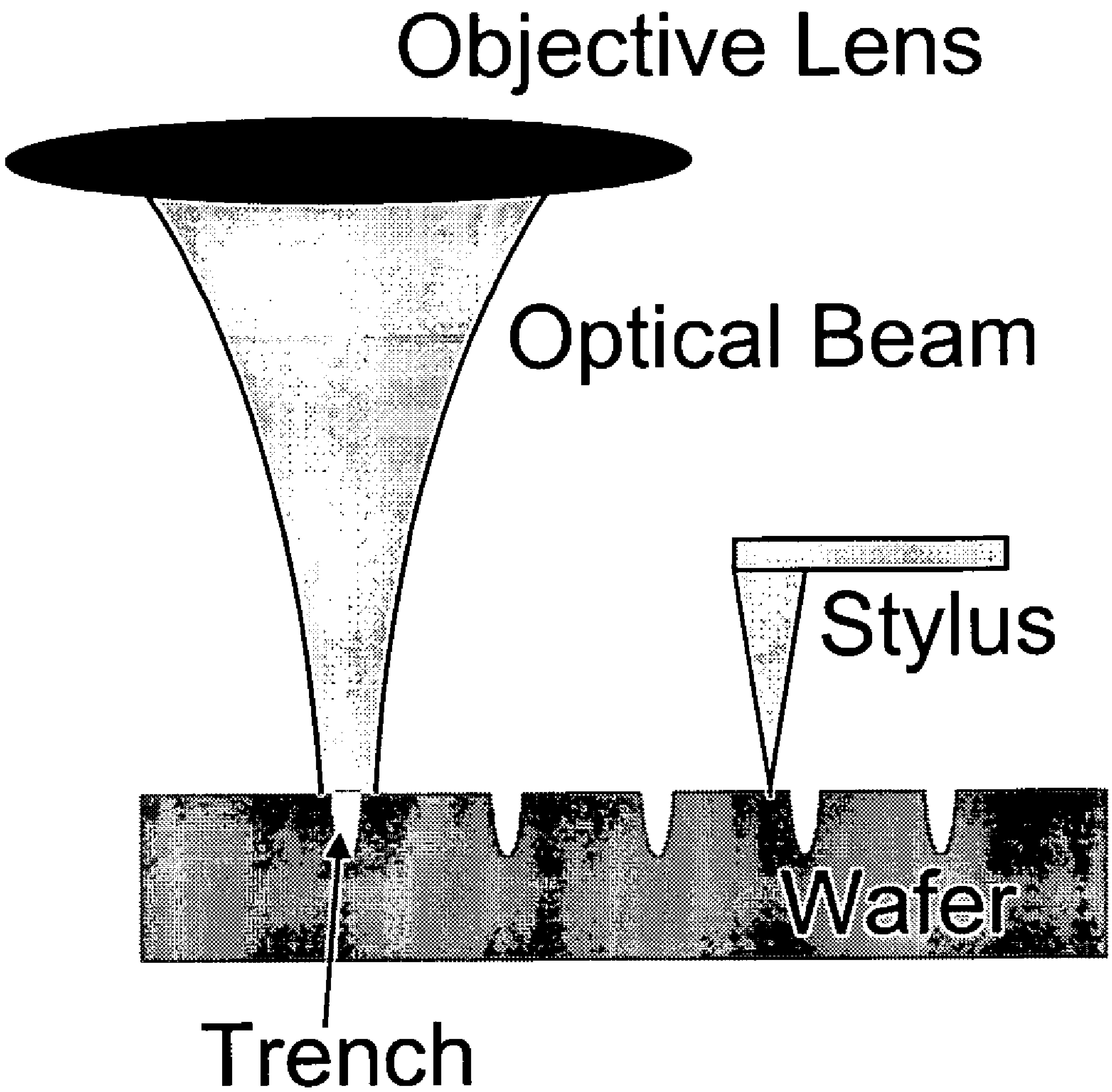


Figure 1

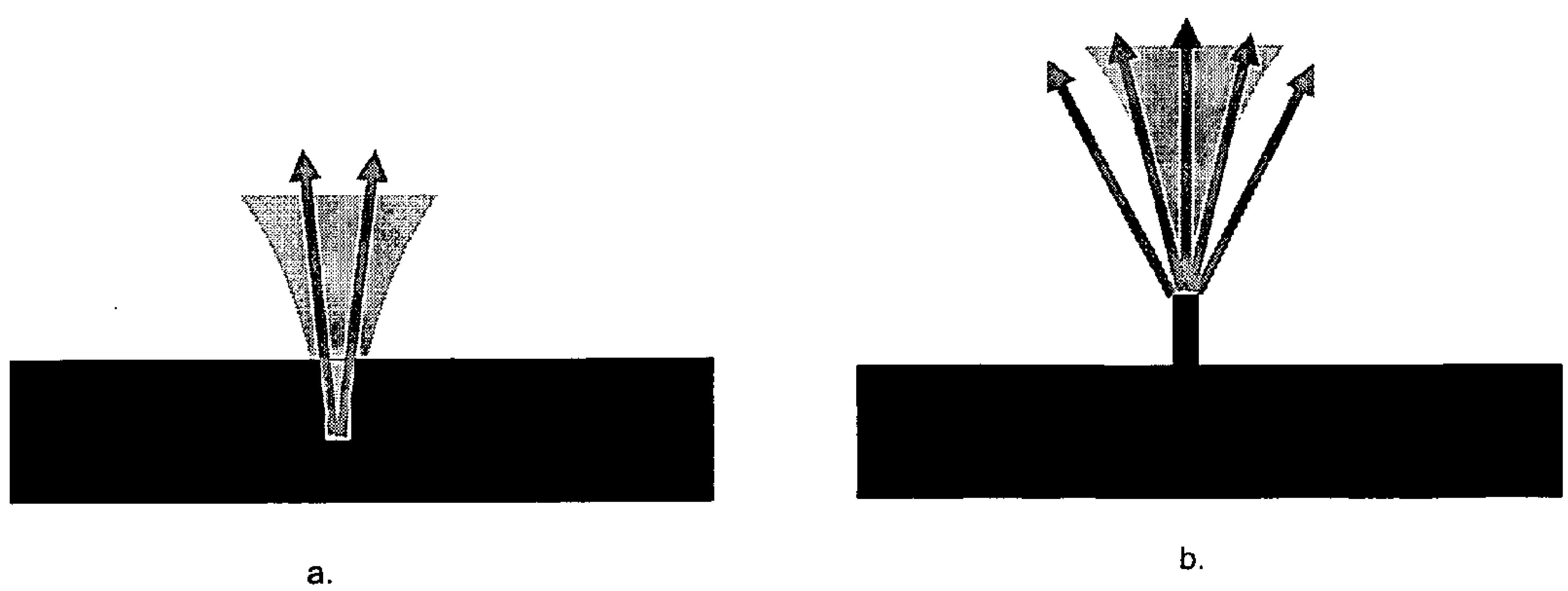


Figure 2

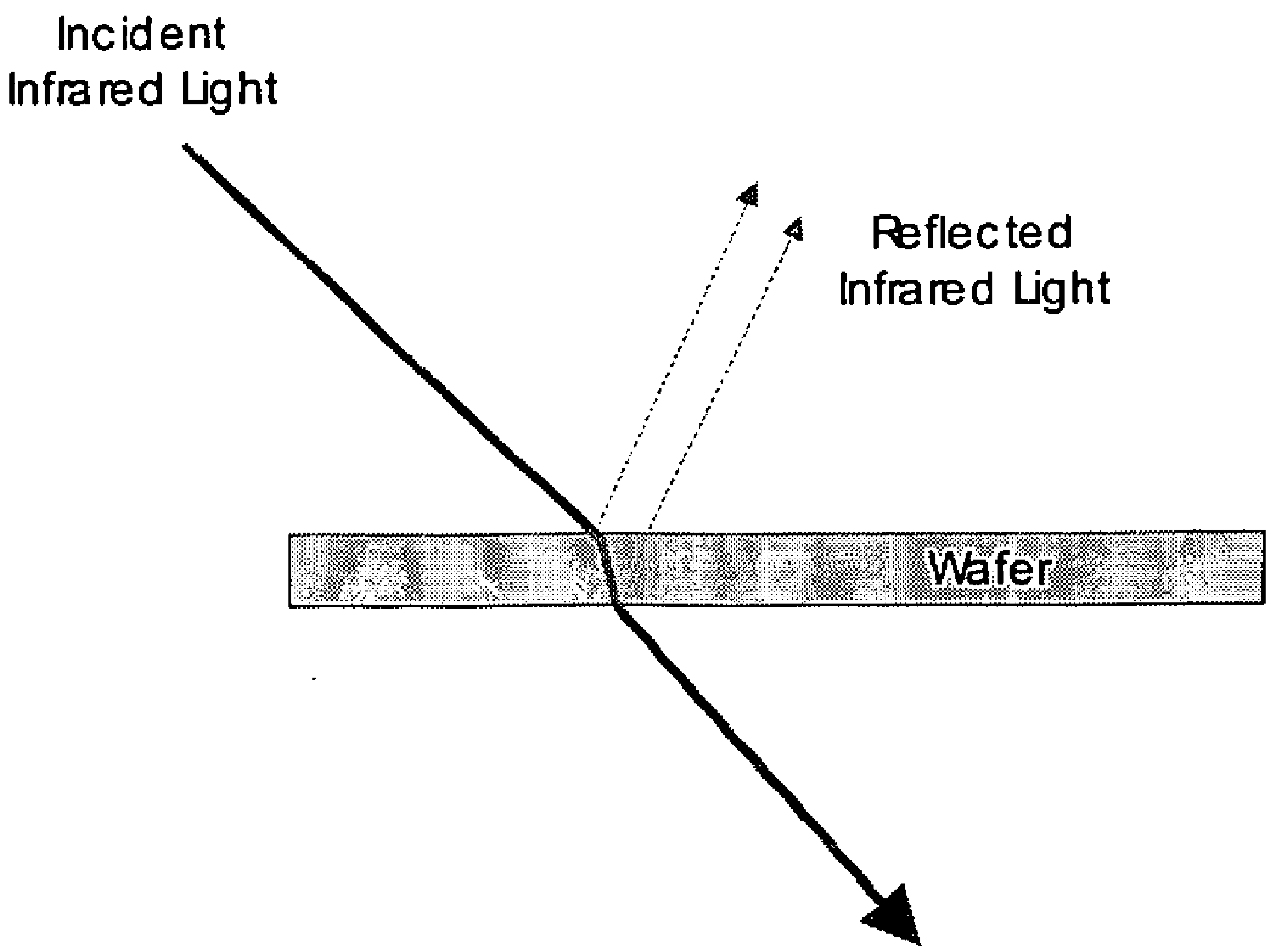
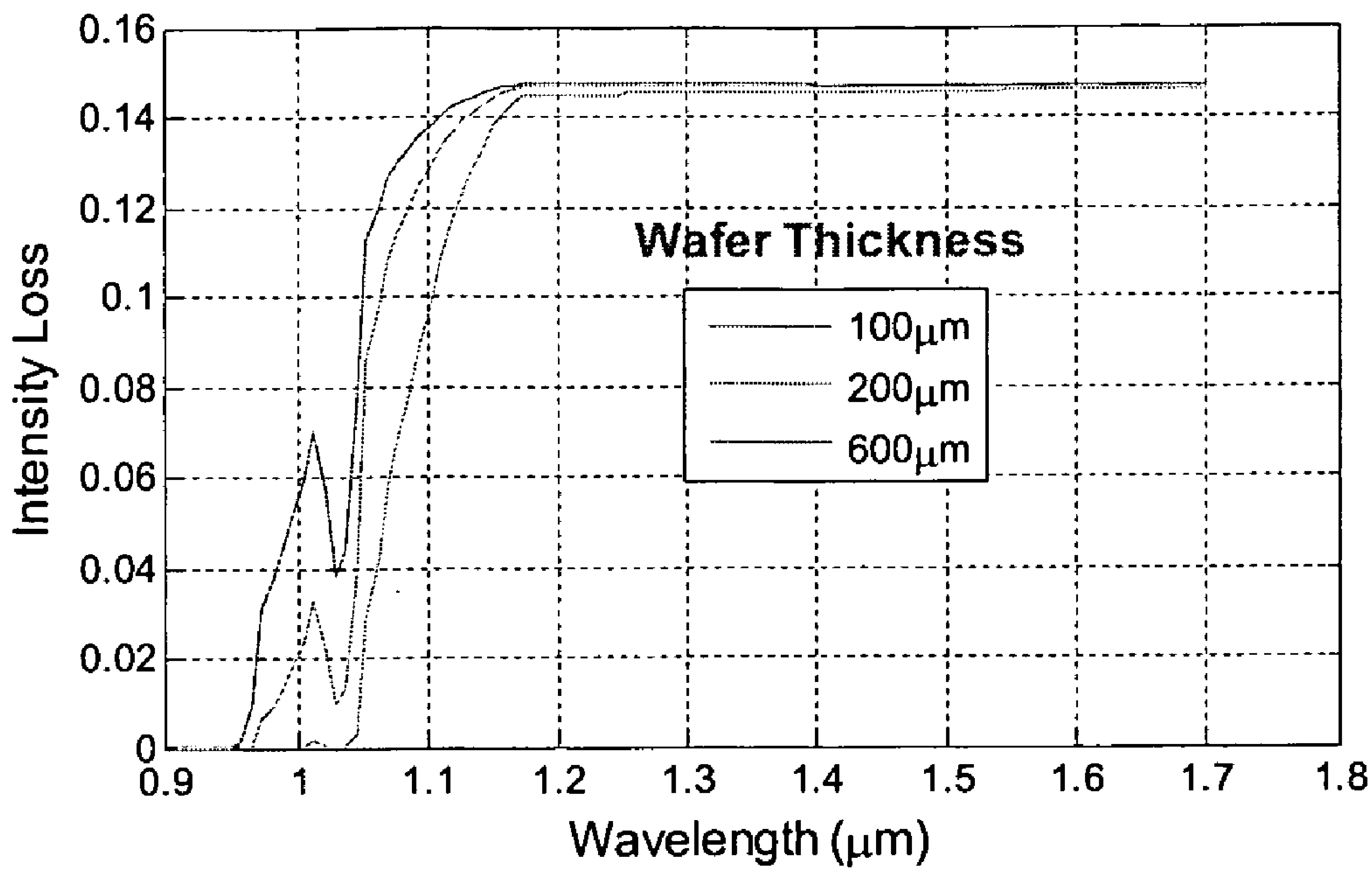


Figure 3



0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Intensity Loss
Wafer Thickness
100μm
200μm
600μm
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
Wavelength (μm)

Figure 4

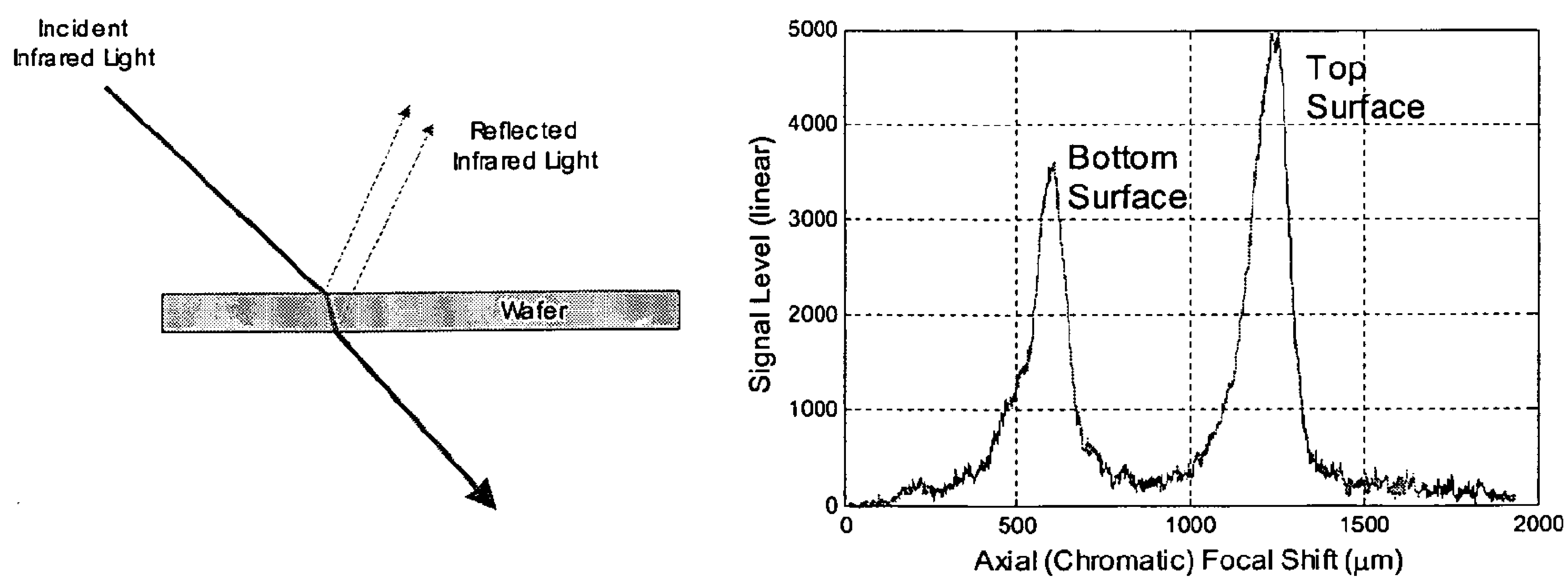

Incident
Infrared Light
Reflected
Infrared Light
Wafer
5000
4000
3000
2000
1000
0
Signal Level (linear)
Top
Surface
Bottom
Surface
0
500
1000
1500
2000
Axial (Chromatic) Focal Shift (μm)

Figure 5

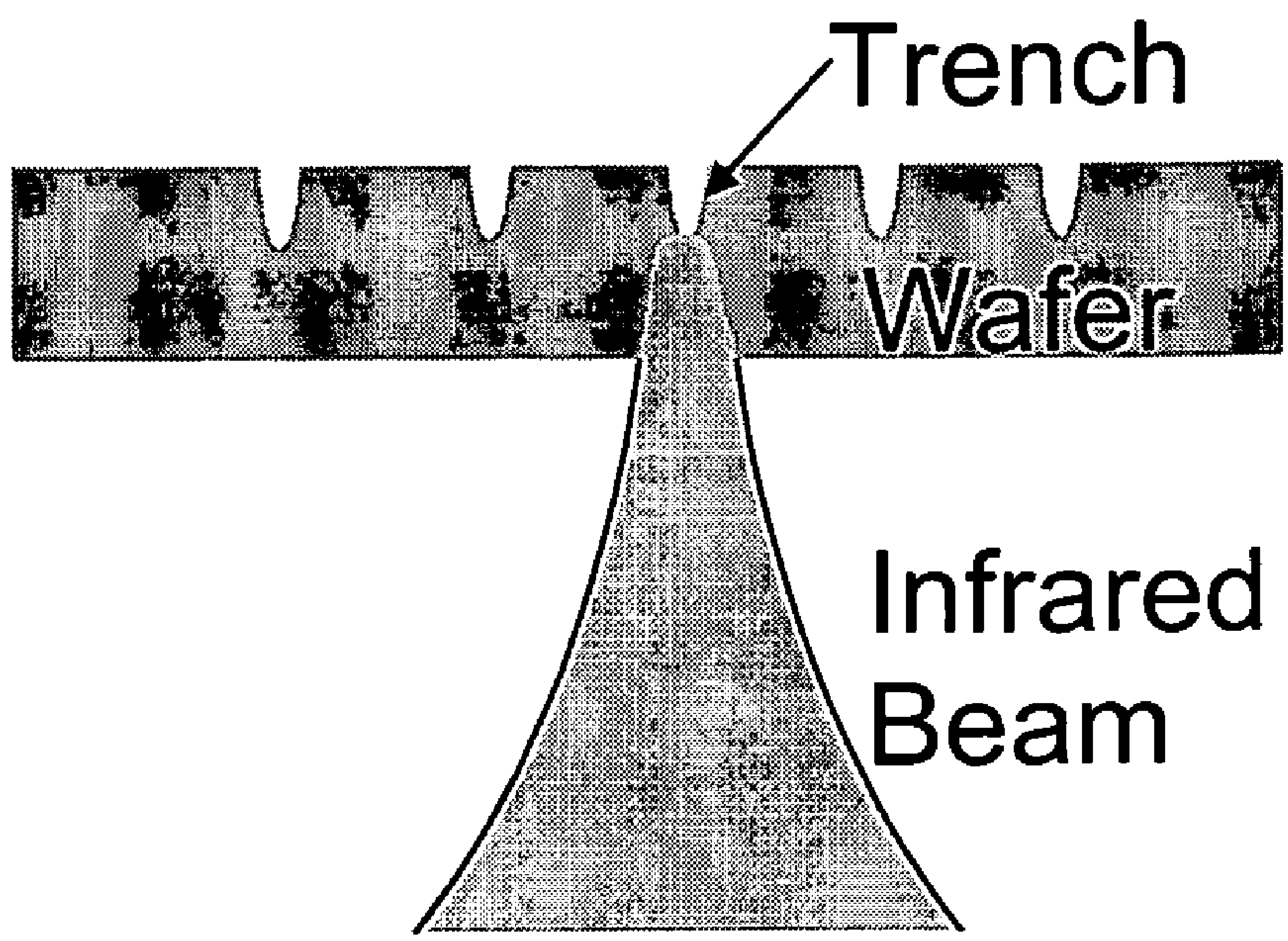


Figure 6

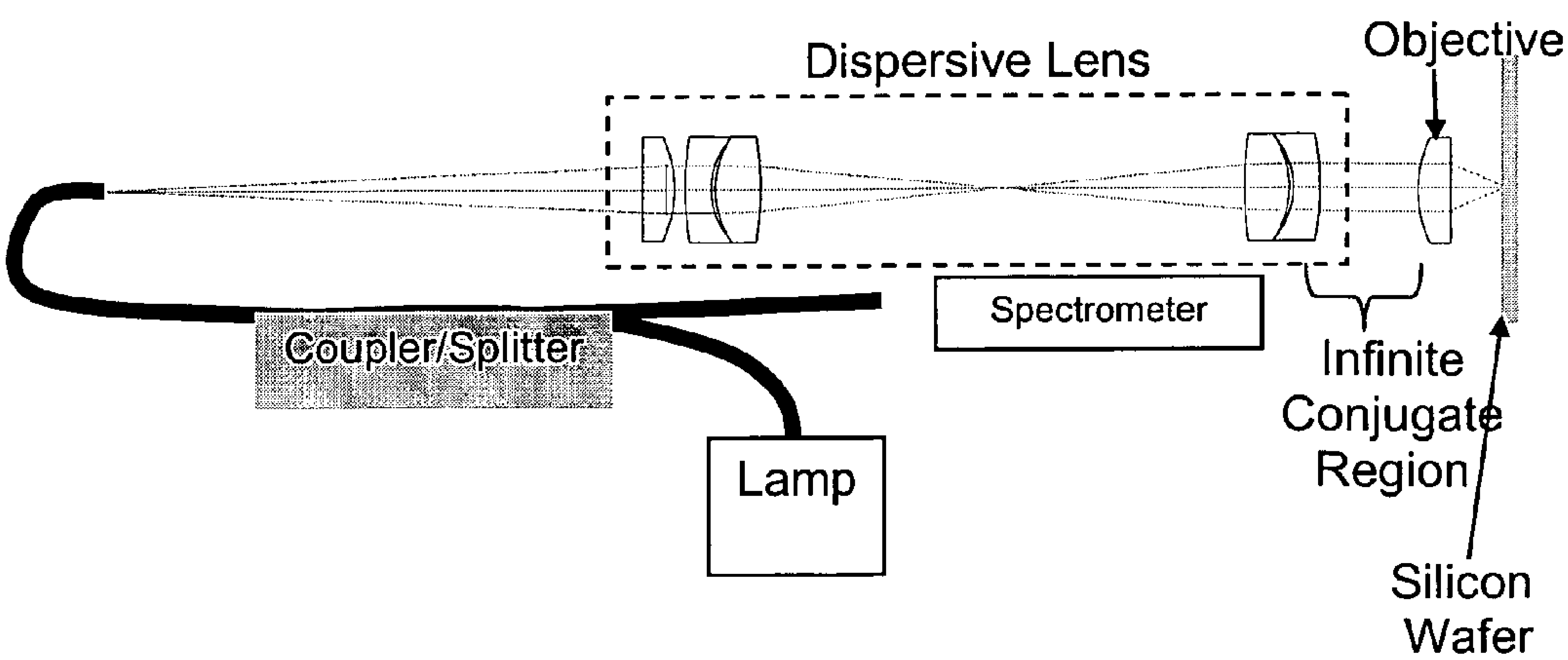

Dispersive Lens
Objective
Coupler/Splitter
Spectrometer
Lamp
Infinite Conjugate Region
Silicon Wafer

Figure 7

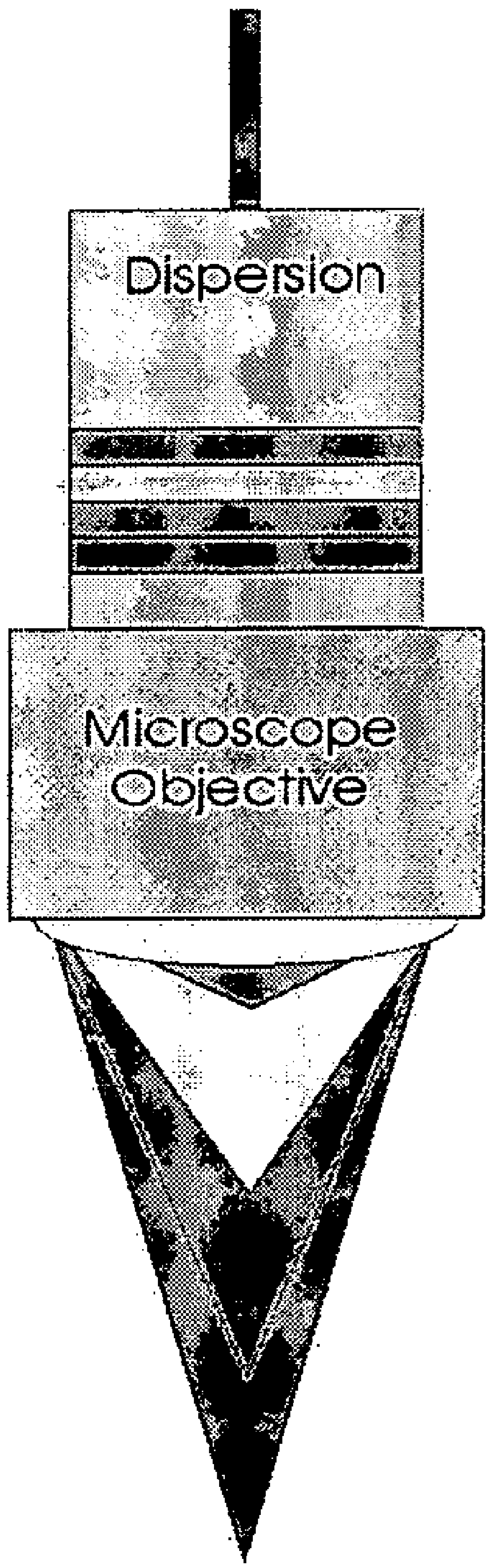


Figure 8

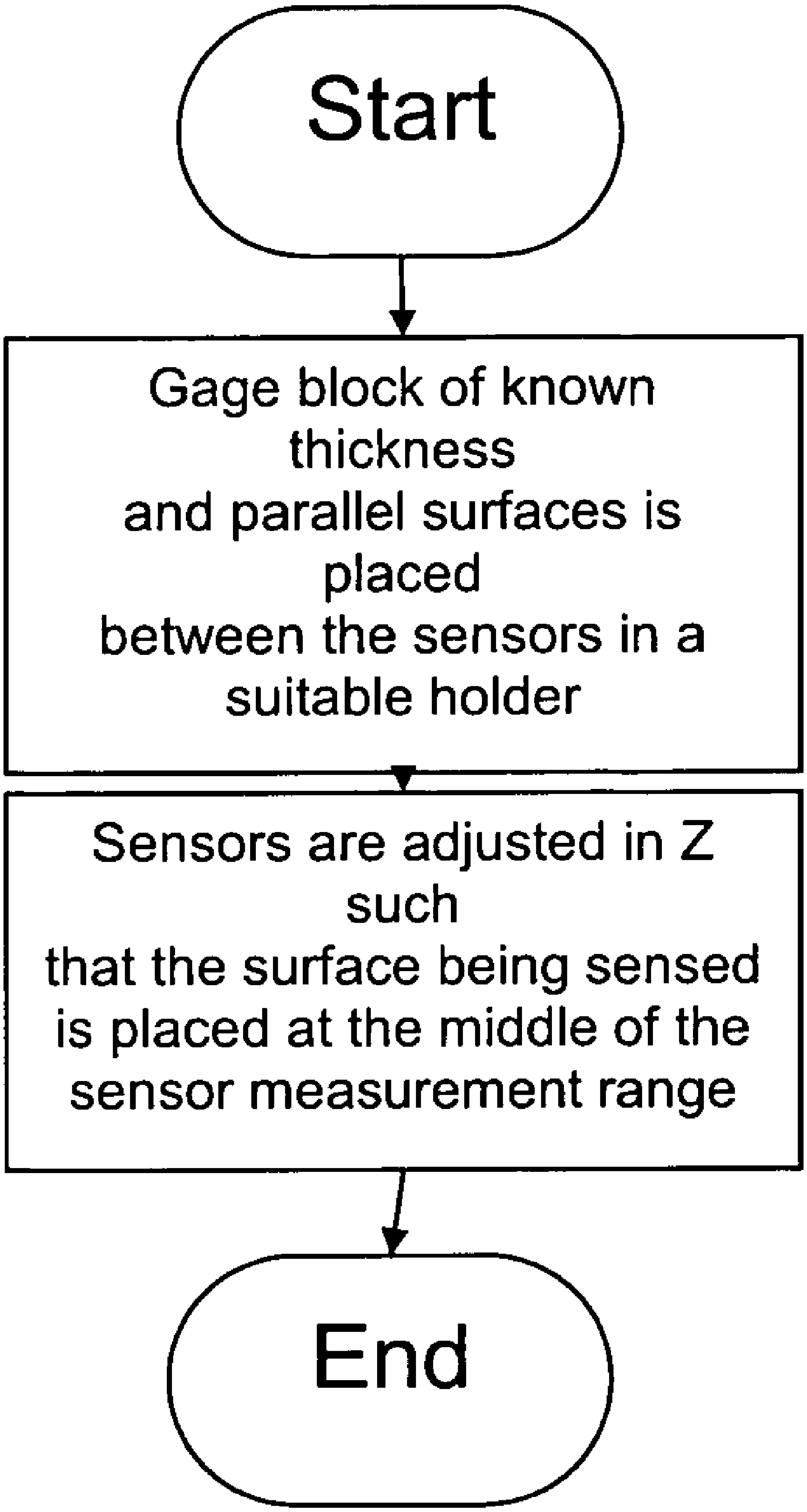

Start
Gage block of known thickness and parallel surfaces is placed between the sensors in a suitable holder
Sensors are adjusted in Z such that the surface being sensed is placed at the middle of the sensor measurement range
End

Figure 9

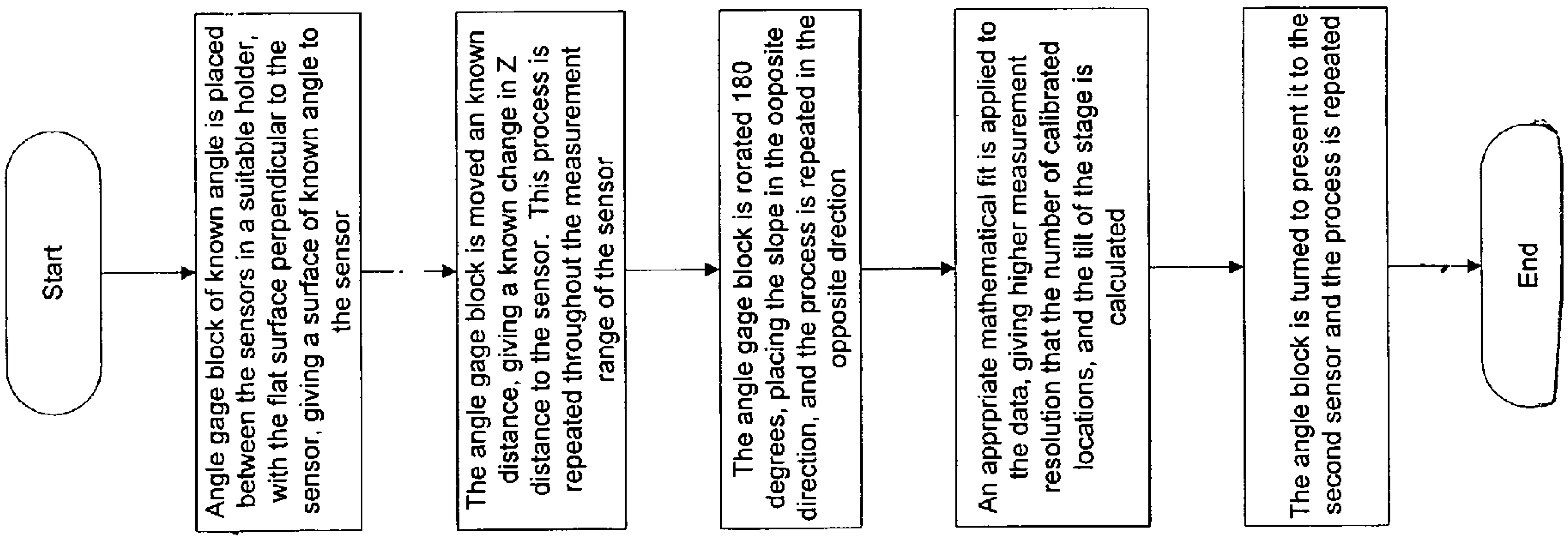

Start
Angle gage block of known angle is placed between the sensors in a suitable holder, with the flat surface perpendicular to the sensor, giving a surface of known angle to the sensor
The angle gage block is moved an known distance, giving a known change in Z distance to the sensor. This process is repeated throughout the measurement range of the sensor
The angle gage block is rorated 180 degrees, placing the slope in the oopposite direction, and the process is repeated in the opposite drection
An apprpriate mathematical fit is applied to the data, giving higher measurement resolution that the number of calibrated locations, and the tilt of the stage is calculated
The angle block is turned to present it to the second sensor and the process is repeated
End

Figure 10

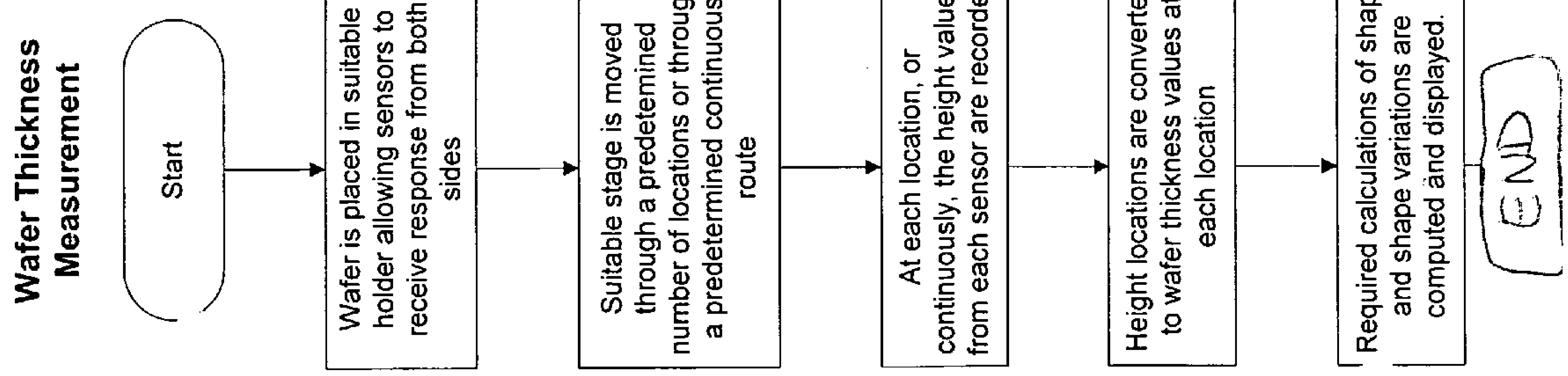

Wafer Thickness Measurement
Start
Wafer is placed in suitable holder allowing sensors to receive response from both sides
Suitable stage is moved through a predetemined number of locations or through a predetermined continuous route
At each location, or continuously, the height values from each sensor are recorded
Height locations are converted to wafer thickness values at each location
Required calculations of shape and shape variations are computed and displayed.
END

Figure 11

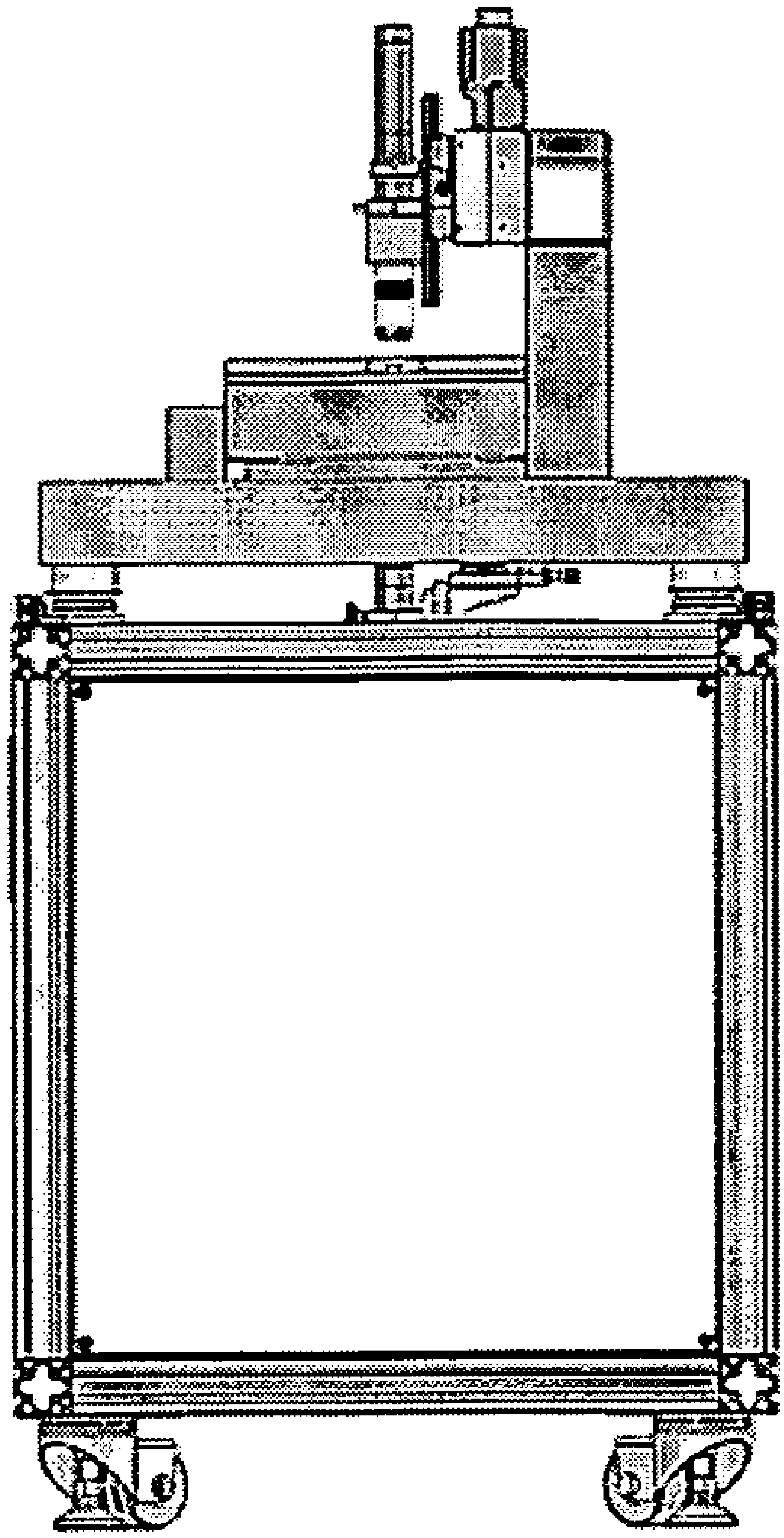


Figure 12

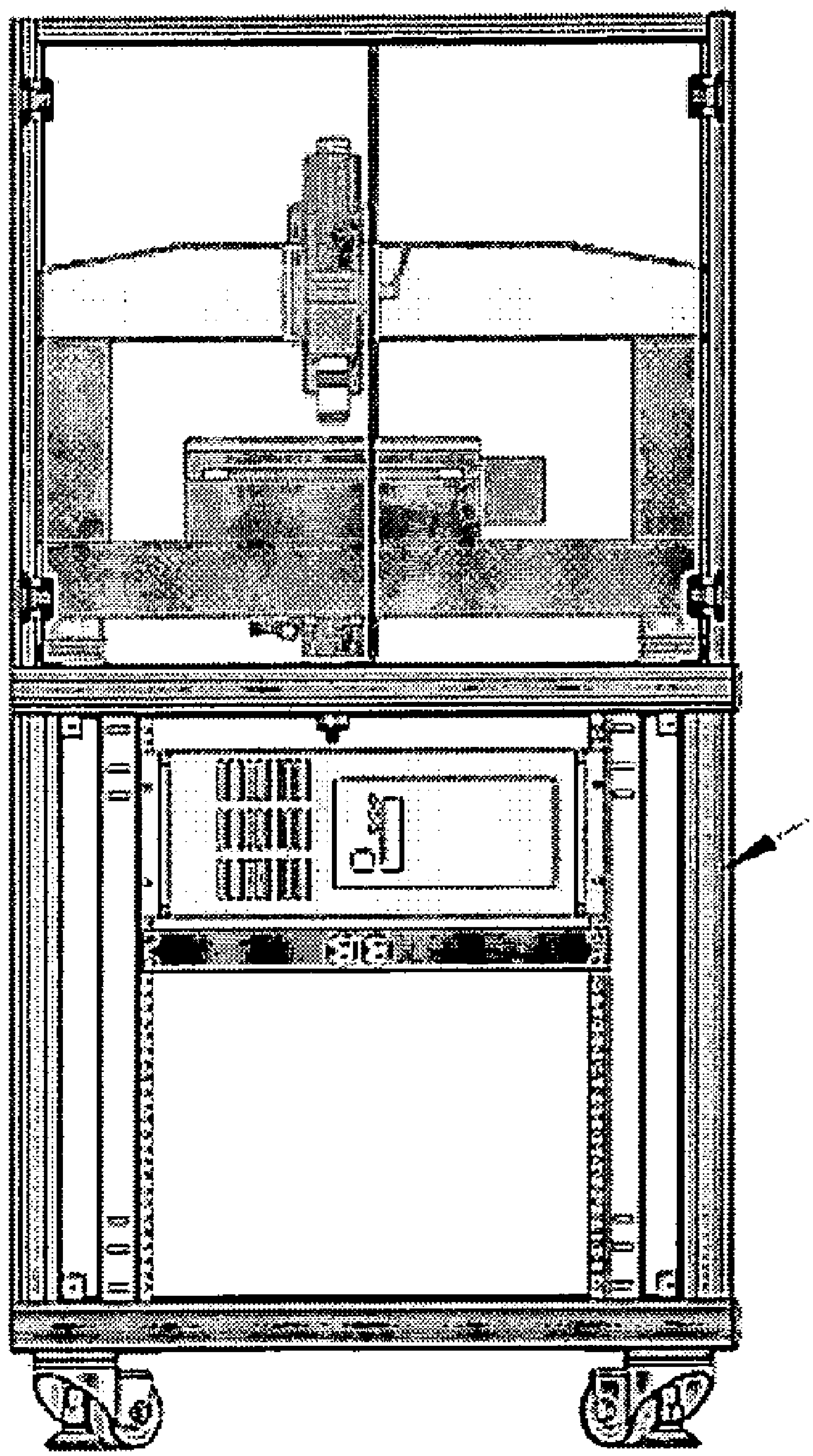


Figure 13

Figure 14

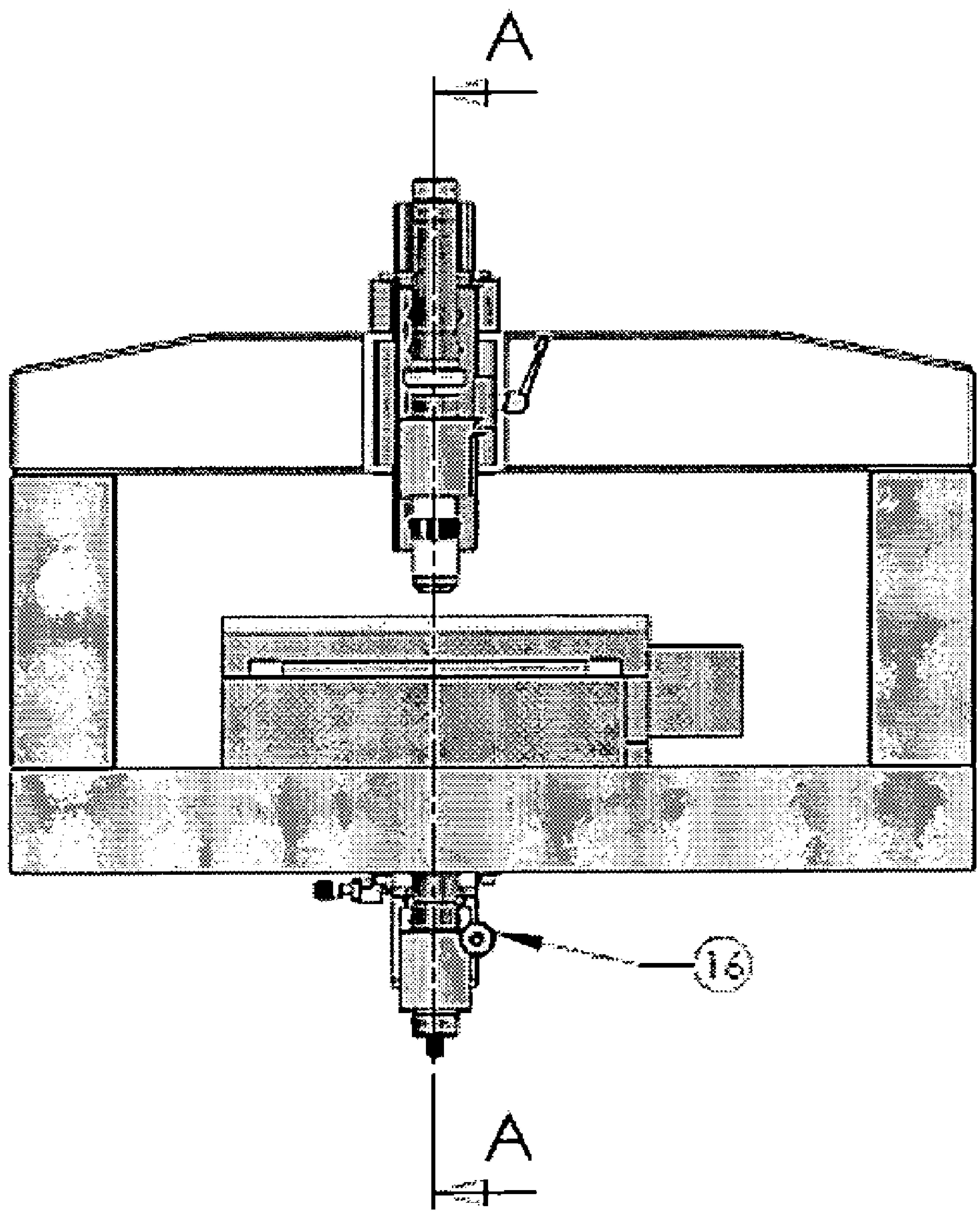
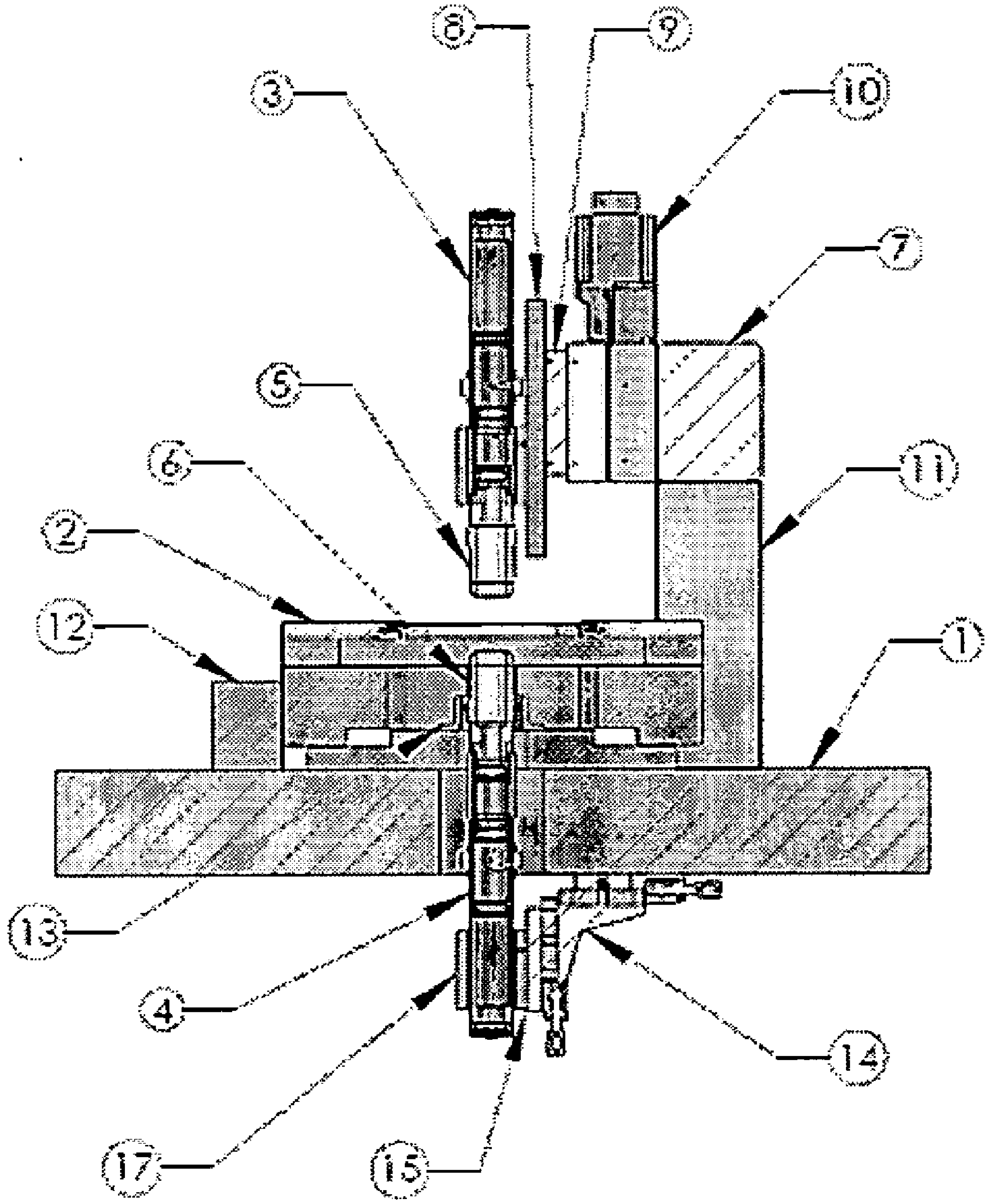
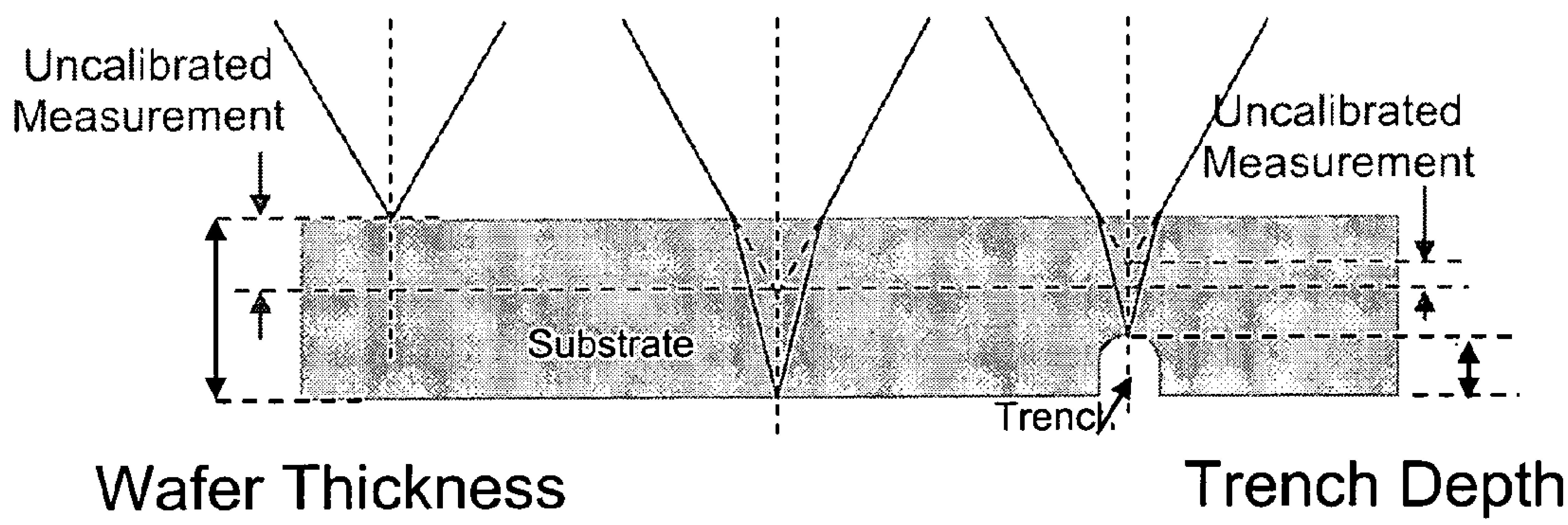


Figure 15



SECTION A-A
SCALE 1 : 6

Figure 16


Uncalibrated
Measurement
Uncalibrated
Measurement
Substrate
Trench
Wafer Thickness
Trench Depth

WAFER MEASUREMENT SYSTEM AND APPARATUS

REFERENCE TO PRIOR APPLICATION

[0001] This application claims the priority of provisional application 60/721,554, filed Sep. 29, 2005 entitled WAFER THICKNESS AND FLATNESS MEASUREMENT SYSTEM by David L. Grant, David S. Marx, Michael A. Mahoney and Tsan Yuen Chen, and provisional application 60/787,639, filed Mar. 31, 2006 entitled IMPROVED WAFER TRENCH DEPTH MEASUREMENT SYSTEM by David S. Marx and David L. Grant and provisional application 60/754,018, filed Dec. 27, 2005 entitled WAFER THICKNESS AND FLATNESS MEASUREMENT SYSTEM by David S. Marx, David L. Grant, Michael A. Mahoney, and Tsan Yuen Chen.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The present invention relates generally to the field of the measurement of silicon wafers used in the production of semiconductors, and particularly to the measurement of the thickness of thin wafers, the flatness and localized shape of thin wafers and the depth of trenches etched thereon.

[0004] 2. Description of the Prior Art

[0005] When making semiconductors, manufacturers start with blank silicon wafers. Many processes are performed on them before the completed semiconductors are complete and a large number of these processes involve placing images of a photo mask on the wafer. The various images must overlay each other with great accuracy. As the size of the features on the wafer shrink, the accuracy with which each layer must overlay increases.

[0006] The size of features being placed on wafers now is at such a tight level that even the shape of the wafer can effect the quality of the photo processes. Imagine a wafer with the shape of a potato chip. The wafer is so warped that the masks can never be aligned because the optical equipment cannot focus on the entire surface at once. This type of problem is costly to semiconductor manufacturers due to reduced yields. An instrument that accurately and reliably measures the flatness and thickness of a wafer would help these manufacturers improve their process and produce better ICs with greater yield.

[0007] The present technique that is most popular for measuring the thickness of a wafer is called a capacitance test. The wafer is placed between two electrodes and the material in between causes a change in capacitance. The change in capacitance is a direct measure of the amount and type of material between the electrodes.

[0008] For many years this technique has worked reliably. The limitations and shortcomings of this technique have only recently become significant as the accuracy of the required measurement increases and the wafers have become significantly thinner.

[0009] One of the shortcomings of this technique is that detailed information is needed about the properties of the wafer material, such as its relative permittivity. This can be problematic if the wafer has multiple materials or is bumped with solder bumps.

[0010] Another shortcoming is that the number of locations where the thickness can be measured is small, due to the relatively large size of the capacitance sensors. Typically the number of locations is about 10 for a 4-inch wafer and about 30 for a 12-inch wafer. A manufacturer would ideally want to know detailed height and thickness information over the entire wafer, not just a small number of locations. Additionally, the accuracy of the measurements is a question as the measurement is essentially an average thickness over the area of the capacitance sensor.

[0011] The area of the capacitance sensor is typically about ½ inch in diameter. More importantly, however, is that the resolution of the capacitance sensors is no longer fine enough to satisfy the increasingly tight requirements of the manufacturers. With late generation wafers having a thickness of between 800 and 200 microns, and expectations that future generations will be as thin as 40 microns, the measurement accuracy needs to be 0.1 micron or smaller.

[0012] Related to the problem of measurement of the thickness of thin wafers is the problem of measuring trench depth on wafers. When processing semiconductor wafers into devices, such as integrated circuits, micro-electro-mechanical systems (MEMS), and integrated photonic devices, manufacturers perform many processes, some of which include etching trenches into the wafer. For many of these devices, the depth of the etched trench is critical to the proper performance of the finished device, and the manufacturers typically desire to measure its depth. However, current methods of measuring the trench are severely limited.

[0013] MEMS products typically contain three-dimensional structures with regions of deep, narrow trenches with near-vertical sidewalls. A typical example is a trench etched 5 microns wide by 100 microns deep. MEMS devices with these characteristics include sensors, actuators, and RF devices such as inductors and comb switches. All of these devices characteristically require deep vertical etching processes to separate moving mechanical parts, and finger-like features are very common.

[0014] Manufacturers of MEMS devices do not currently have an accurate and inexpensive method to non-destructively measure the depth of etched high aspect ratio trenches. They need to have precise control over etch depth to produce a working device, and the measurement of etch depth is very important for process development and control. Current metrology technology cannot measure the depth of high aspect ratio trenches with speed and accuracy. Thus, the development of a non-contact metrology instrument that quickly and accurately measures the etched depth of high aspect ratio trenches, such as those formed by narrow finger-like structures, would greatly benefit MEMS manufacturers in process development and control.

[0015] Integrated circuits often require deep trenches etched in the wafer to electrically isolate neighboring circuit devices, such as transistors. Space on the wafer is always an important consideration, and yet the trench must be deep enough to provide the required isolation. Thus, the aspect ratio of these etched trenches is increasing with improvements in technology. Currently, these trenches can be one micron or smaller wide and six microns or more deep. In addition, these trenches typically have rounded or rough bottoms that absorb any incident light. Manufacturers need to measure the depth of these trenches for process control and characterization. Currently, the only method to measure these trenches involves destructively cutting the wafer.

[0016] Integrated photonics devices are typically fabricated on materials other than silicon, or in layers of materials "grown" on top of silicon. Examples are SiC, InP, GaAIAs, and silicon nitride. These devices are etched structures to form waveguides, lasers, and other photonic devices. The shape parameters of the etched structures are very important to the performance of photonic devices. The current invention relates to the measurement of deep trenches in a wide variety of materials, such as the above examples as well as the thickness of the wafer.

[0017] Because of the very steep sidewalls inherent in such trench structures, profiling instruments that use a stylus or other method of contact cannot accommodate an aspect ratio or lateral dimension of this nature. For example, atomic force microscopes (AFM) and stylus profilers are not suitable because even if the tip could penetrate the trench, it would not be able to follow the side wall, and the tip would break when exiting the trench.

[0018] Standard non-contact optical instruments for measuring surface height are confocal microscopes, white light interferometers, phase shift interferometers, and triangulation techniques. All of these optical techniques involve some manner of illuminating the trench and analyzing the reflected light. However, the steep walls of the trench prevent much of the light from reaching the bottom of the trench. In addition, some etched trenches may have rounded or rough bottoms. The light that enters these trenches might be completely absorbed. If there is no light returned, then no method of analysis can possibly determine the depth of the trench. Aside from these fundamental problems, each of the listed non-contact methods has problems unique to that particular method.

[0019] Standard confocal microscopes fail because they confuse the signal from the top of the trench with the signal from the bottom when the trench is too narrow. When the width of the trench approaches the size of the source pinhole, as much or more light will be detected when the focus is on top of the trench as when it is at the bottom. Thus, a confusing signal is generated even when the bottom of the trench is far away from the focal plane. Confocal microscopes are also very slow since they require scanning the measurement sample axially to find the plane of best focus.

[0020] White light interferometers have similar difficulties in that they are slow and must scan axially. In addition, the fringe signal is weak due to the light scattered from the walls and the top. Phase shift interferometers fail outright because phase unwrapping fails to detect steep sidewalls. Finally, triangulation techniques can only succeed if precise control of the direction of the incident beam relative to the direction of the trench is maintained so that the light can get into the trench from the side. This constraint makes such an instrument infeasible.

[0021] All of the prior art methods described above have in common the fact that they attempt to measure the trenches from above, that is, the optical beam or mechanical stylus approaches the trench from the same side as the surface that was etched.

SUMMARY OF THE INVENTION

[0022] The preferred embodiment of the present invention teaches a method for measuring the trench depth of a wafer. The steps in the method include microscopically locating a trench on a wafer that has a front surface and a back surface such that the trench is on the front surface; positioning a non-contact optical instrument facing the back surface so that the trench is effectively a bump on the second surface from the non-contact optical instrument, the non-contact optical instrument utilizing a light source such that the wafer is transparent and the non-contact optical instrument receives reflected light from the back surface and the front surface on the wafer such that the front surface indicates the interior of a trench; taking the measurement of the height of the bump using a chromatic confocal sensor set in a wavelength range wherein the wafer is transparent; calibration of the bump height through a conversion of the measured height differences between the measured reflected wavelengths of the top surface and the bottom surface thereby determining the shape and contour of the wafer at the site of the trench.

[0023] A second embodiment involves a method for measuring localized thin wafer thickness. The steps include microscopically locating the localized thickness area on the trench on the wafer, with the wafer having a front surface and a back surface; positioning a chromatic confocal sensor on one side of the wafer to receive reflected light from the top surface and the bottom surface simultaneously; using a wavelength range wherein the wafer is transparent; calibration of the localized wafer thickness through a conversion of the measured height differences between the measured reflected wavelengths of the top surface and the bottom surface thereby determining the localized thickness of the wafer.

[0024] A third embodiment is an apparatus for measuring trench depth on a wafer or localized thickness of a wafer, the wafer having a top side and a bottom side, the apparatus comprising a non-contact optical height measurement instrument; a securing means located substantially beneath the non-contact optical height measurement instrument for positioning of the wafer; a light source set in a wavelength range wherein the wafer is transparent; the non-contact optical instrument is positioned on one side of the wafer to receive reflected light from the top surface and the bottom surface simultaneously; calibration means that converts the collected data from the non-contact optical height sensor to the distance to the top and bottom surfaces.

[0025] All three embodiments above can use a silicon wafer wherein the light source is in the near infrared region, having a wavelength in the range of 900 nm to 1700 nm, or utilize GaAs, GaAIAs, InP, SiC, SiO_2 and the like.

[0026] All three embodiments above can use as a non-contact optical instrument any one of the following: a chromatic confocal sensor, white light interferometery, phase shift interferometry, scanning confocal microscopy and laser triangulation. Using chromatic confocal sensors for trench measurement is the subject of U.S. Patent Application No. 2006/0109483 by inventors Marx and Grant of the present invention, the technology therein being fully incorporated herein by reference. Measurement by chromatic confocal sensors is achieved through the use of axial dispersion so that each wavelength focuses at a different distance. The sensor then measures distance to the reflecting surface by determining the wavelength of light best reflected.

[0027] The embodiments above can be further modified by defining a calibration means is utilized by the non-contact chromatic confocal non-contact height instrument that converts the collected data corresponding to the wavelengths of the reflected light from the top surface and bottom surface of the wafer and the corresponding height differences into a measured thickness that determines the depth of the trench, or the thickness of the localized area on a wafer.

[0028] The embodiments above can be further modified by defining that the optical instrument used mechanically scans the wafer in transverse directions at a pre-specified sample rate and density.

[0029] Another embodiment of the present invention involves a method for measuring the thickness, flatness and localized shape of a thin wafer. The thin wafer has a top side and a bottom side. The method includes calibrating the distance of the wafer from a first sensor and a second sensor. The calibration further comprises placing a gage block of a known thickness and containing parallel surfaces between the first and second sensors in a suitable holder. The first and second sensors are then adjusted in the Z plane such that the surface being sensed is placed at the middle of the sensor measurement range.

[0030] The height response of each height sensor is calibrated separately. The sensor height is then calibrated by the first placement of an angle gage block of known angle between the first and second sensors in a suitable holder with the flat surface of the angle gage block being perpendicular to the first sensor, giving a surface of known angle to the first sensor. Then the angle gage block is rotated 180 degrees, placing the slope of the angle gage block in the opposite direction from the first placement with the angle gage block being perpendicular to the first sensor, giving a surface of known angle to the first sensor.

[0031] The height sensor calibration is then converted mathematically, thereby calculating the tilt of the angle block. The angle gage block is then turned to present the angle gage block to the second sensor, repeating steps as applied to the first sensor. The localized thickness of the wafer is measured, with the measurement step further comprising placement of the wafer in a suitable holder allowing the first and second sensors to receive responses from both sides of the wafer.

[0032] The wafer in the suitable holder is then moved through a predetermined number of locations either individually at each of the locations or continuously. The height values are then recorded at each of the locations or continuously. The height values are then converted to thickness values at each of the locations or continuously. The shape and variations of the wafer are computed through a mathematical calculation and the resulting values are displayed through a displaying means, such as a computer screen.

[0033] Another embodiment of the invention is an apparatus for measuring the thickness, flatness and localized shape of a thin wafer. The wafer has a top side and a bottom side. The apparatus comprises a first stage for calibrating the distance of the wafer from a first sensor and a second sensor. The distance calibration further comprises placing a gage block of a known thickness and containing parallel surfaces between the first and second sensors in a suitable holder.

[0034] The first and second sensors are adjusted in the Z plane such that the surface being sensed is placed at the middle of the sensor measurement range. There is a second stage for calibrating the sensor height, with the sensor height calibration further comprising the first placement of an angle gage block of known angle between the first and second sensors in a suitable holder with the flat surface of the angle gage block being perpendicular to the first sensor, giving a surface of known angle to the first sensor.

[0035] The angle gage block is then rotated **180** degrees, placing the slope of the angle gage block in the opposite direction from the first placement with the angle gage block being perpendicular to the first sensor, giving a surface of known angle to the first sensor. The height sensor calibration is collected mathematically, thereby calculating the tilt of said angle block.

[0036] The angle gage block is then turned to present the angle gage block to the second sensor, repeating steps as applied to the first sensor. Then there is a third stage for measuring the localized thickness of the wafer, the thickness measurement further comprising placement of the wafer in a suitable holder allowing the first and second sensors to receive responses from both sides of the wafer.

[0037] The wafer is then moved in said suitable holder through a predetermined number of locations either individually at each of the locations or continuously. The height values at each location or continuously are recorded and the height values converted to thickness values at each of the locations or continuously. The shape and shape variations of the wafer are then calculated through a mathematical calculation, with the calculation results being displayed through a displaying means, such as a computer screen.

BRIEF DESCRIPTION OF THE DRAWINGS

[0038] FIG. **1** is a view of the prior art technique for the measuring wafer thickness and trench depth.

[0039] FIG. **2** includes a first diagram that shows incident light and reflected light on a trench and a second diagram that shows incident and reflected light on a bump.

[0040] FIG. **3** demonstrates how light is reflected from both the top and bottom surfaces of a silicon wafer.

[0041] FIG. **4** a wavelength vs. intensity loss graph that demonstrates light intensity reflected from the bottom surface of a silicon wafer relative to the intensity of the incident light, for each wavelength in the near infrared spectrum. Note how silicon absorbs light with wavelengths shorter than approximately 1.1 μm.

[0042] FIG. **5** demonstrates an experiment for wafer thickness showing how when a chromatic confocal sensor is operating in the visible spectrum, it simultaneously measures the axial separation between the top and bottom surfaces of a glass microscope slide.

[0043] FIG. **6** is a diagram that shows the preferred embodiment of the instant invention as it uses an infrared beam to look through the back of a wafer, thereby effectively rendering the depth a bump as viewed from the back.

[0044] FIG. **7** shows a schematic view of a chromatic confocal system for the measurement of trenches.

[0045] FIG. **8** shows the optical stylus of the present invention.

[0046] FIG. **9** is a flow chart demonstrating the sensor distance calibration for thin wafer thickness measurement.

[0047] FIG. **10** is a flow chart demonstrating the sensor height calibration for thin wafer thickness measurement.

[0048] FIG. **11** is a flow chart demonstrating the wafer thickness measurement steps for thin wafer thickness measurement.

[0049] FIG. **12** is a side view of the apparatus for measuring wafer thickness and flatness.

[0050] FIG. **13** is a front view of the apparatus for measuring wafer thickness and flatness.

[0051] FIG. **14** is close up view of the apparatus for measuring wafer thickness and flatness.

[0052] FIG. **15** is a cross section view of the area marked A-A in FIG. **14**.

[0053] FIG. **16** illustrates how the index of refraction of a silicon medium affects measurement calibration.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

[0054] The instant invention seeks to measure thin wafer thickness as well as the depth of any trench etched thereon. An optical stylus is used that can be thought of as a stylus of light. The stylus has a different color focus at different levels. Thus, any part that reflects the light of the optical stylus will only reflect color that is in focus. FIG. **8** shows the optical stylus. The system then relates color to height. The stylus scans the wafer with whatever density is required by the user, thus acquiring thousands and potentially tens of thousands of data points by which the surface can be defined.

[0055] Regular wafers, i.e., those wafers that have sufficient mass to support their own weight, can be measured by using two optical styli, one from the top and one from the bottom. The separate surfaces acquired by the two styli are related to each other through a calibration operation. Thus, the system can determine the shape and calculate warp, bow, and various other shape values of interest to the manufacturer. Manufacturers can now verify that the wafer is flat enough for processing.

[0056] Thin wafers, which are used in heat sensitive applications, can often not support their own weight if held by the sides. The wafers are actually conformal, meaning they conform to the surface upon which they are sitting, assuming sufficient vacuum, whereas the thick wafers will not. Thick wafers maintain their shape.

[0057] Thin wafers still need to be measured for proper thickness and shape because the thickness is critical to heat processing. Additionally, the top and bottom surfaces need to be parallel. Therefore, for thin wafers, a flat vacuum chuck is required to secure the wafer and the surface is measured only from the top. The system will measure the surface of the vacuum chuck in a calibration procedure and reference the surface of the vacuum chuck to determine the surface shape, thickness and parallelism.

[0058] As seen in FIG. **9**, the steps involved in calibrating the distance from the sensor involve first placing a gage block of known thickness and parallel surfaces between the sensors in a suitable holder. Then the sensors are adjusted in the Z plane such that the surface being sensed is placed at the middle of the sensor measurement range.

[0059] As seen in FIG. **10**, steps involved in calibrating the sensor height involve first placing an angle gage block of known angle between the sensors in a suitable holder with the flat surface perpendicular to the sensor, giving a surface of known angle to the sensor. Then, the angle gage block is moved a known distance, giving a known change in the Z plane distance to the sensor. This process is repeated throughout the measurement range of the sensor. The angle gage block is then rotated 180 degrees, placing the slope in the opposite direction, and the process is repeated in the opposite direction. An appropriate mathematical fit is applied to the data, giving higher measurement resolution than the number of calibrated locations, and the tilt of the stage is calculated. Finally, the angle block is turned to present it to the second sensor and the process is repeated.

[0060] FIG. **11** demonstrates the steps in measuring wafer thickness. First the wafer is placed in a suitable holder allowing the sensors to receive responses from both sides. Then the suitable stage containing the wafer is moved through a predetermined number of locations or through a predetermined continuous route. At each location, or continuously, the height values from each sensor are recorded. Height locations are converted to wafer thickness values at each location. Required calculations of shape and shape variations are then computed and displayed.

[0061] The thickness and flatness measurements are made on an apparatus illustrated in FIGS. **12-15**. A frame **18** holds the entire apparatus. FIG. **15** shows each component part in detail. The granite base **1** is the principle structural support for the entire system. The vacuum chuck **2** holds the wafer to be measured and uses vacuum to keep the wafer stationary.

[0062] The height sensor top **3** is an optical stylus as described in U.S. Patent Application No. 2006/0109483 to Grant and Marx. The sensor, along with the objective lens measures the top surface of the wafer. The height sensor bottom **4** is another optical stylus sensor that measures the bottom surface of the wafer.

[0063] There is an objective lens **5** for the top sensor and another objective lens **6** for the bottom sensor. A granite bridge **7** provides granite structural support for mounting the top sensor over the wafer. A dovetail mount **8** is used as a transfer plate for mounting the top sensor to the motorized stage **10**.

[0064] A clamp **9** clamps the dovetail mount **8** and mounts to the motorized stage **10**. The motorized stage **10** is for moving the top sensor **3** closer or further away from the wafer. The top sensor **3** is moved so that the top surface of the wafer is within the sensor's **3** measurement range. After this movement, the separation between the top and bottom sensors is calibrated.

[0065] Granite columns **11** provide structural support for the granite bridge **7**. A 6"×6" motorized stage **12** is used to move the wafer in the plane between the top **3** and bottom sensors **4**. Wafer thickness and flatness is measured by recording the top **3** and bottom **4** sensor measurements while this stage **12** is translating the wafer.

[0066] A stage bracket **13** is used to provide structural support for the bottom sensor **4**. The XYZ stage **14** provides an alignment for the bottom sensor **4**. A microscope mount bracket **15** transfers the plate to mount the bottom sensor **4** to the XYZ stage **14**. A cinch stud **16** tightens the bracket **17** that holds the optical stylus sensors **3**, **4** and mounts to the dovetail mount **8** or the microscope mount bracket **15**. The frame **18** creates a table for supporting the granite base **1** and also holds any required electronics accessories.

[0067] Many optical systems that are not capable of measuring the depth of a trench are well capable of measuring the height of a bump. In contrast to a trench, the incident light on a bump is not even partially blocked. FIG. **2** illustrates this difference in how light is reflected when transmitted into a trench versus how it is reflected when it is transmitted onto a bump. As can be seen from the diagram, reflected light from the bump creates more data points than light reflected from a trench, thereby giving a more accurate reading. The light reflected from the top of a bump returns directly to the sensor without a chance of multiple reflections. No matter how tall the bump, its reflection properties will be similar, unlike a trench where deep trenches inherently reflect less light because of the obstruction of the side walls.

[0068] While a rounded and rough trench might absorb all of the incident light, a rounded and rough bump will always reflect some light. (See FIG. **6**.) In fact, no matter how narrow the bump is at its apex, it will always reflect some light. All of these differences indicate that a bump is much easier to measure than a trench. An etched trench viewed from the reverse side appears as a bump to the sensor, and so its height (depth) becomes much easier to measure.

[0069] Most optical height measuring systems currently on the market typically operate using visible light. However, silicon is opaque to visible light. FIG. **5** shows the instant invention as it operates in the visible spectrum as it measures the thickness of a glass slide. The instant invention, however, uses infrared light, specifically light with wavelengths longer than 950 nm, where silicon is transparent. While specifically discussed herein is silicon, as it is the most common wafer substrate, the present invention can be used for wafers of many different materials, such as glass, SiC, InP, GaAs, and any transparent material. The following discussion assumes infrared light as the source, but the present invention can use any wavelength band where the material of interest is transparent.

[0070] Silicon is transparent to wavelengths longer 1.1 μm. (See FIG. **4**.) The index of refraction of silicon at a wavelength of 1.1 μm is approximately 3.5, and so the reflection of a normally incident beam of light at an air/silicon interface is approximately 31%. The remainder of the light transmits light through the silicon. A similar percentage of transmitted light reflects off the bottom silicon/air interface. Thus, a single sensor positioned on one side of a silicon wafer can receive reflected light from both the top and bottom surfaces of the wafer. FIG. **3** shows the relative signal level received from the bottom of a silicon wafer after propagating through the wafer twice (incident and reflected).

[0071] As shown in FIG. **6**, the preferred embodiment illuminates the wafer on the side opposite that of the etched trenches. Since the wafer is transparent, light is reflected back from the surface where the trenches are etched. Thus, a non-contact height sensor will be able to measure the contour of the trenched surface using the reflection from that surface. Since the trenches appear as bumps from this view, none of the disadvantages inherent when viewed as a trench, such as the trench sidewalls absorbing light, are faced.

[0072] While many different non-contact optical sensors can be used in the present invention to measure the height of the bumps (depth of the trenches), the preferred embodiment utilizes a chromatic confocal sensor, schematically laid out in FIG. **7**. Other possibilities are: white light interferometry, phase shift interferometry, scanning confocal microscopy, and laser triangulation. The preferred embodiment is specifically designed to utilize a chromatic confocal sensor and to operate in the near infrared (NIR) region of the spectrum, from 900 nm to 1700 nm to measure the thickness of a wafer by simultaneously measuring the distances to the top and bottom surfaces. The method of calibration, relating the measured separation between the two reflected waves to actual wafer thickness, is not obvious and is an integral part of this invention. As discussed previously, a similar system can also measure trench depth by simultaneously measuring the distances to the top and bottom surfaces.

[0073] Chromatic confocal sensors are well known to those familiar with the art of optical measurements, and specific embodiments are described in U.S. Patent Application 2006/0109483 to two of the present inventors Marx and Grant, the technology therein being fully incorporated herein by reference. This type of sensor spreads a focused spot along the axial direction according to the color, or wavelength, of the light (FIG. **7**). Thus, each wavelength focuses at a different level, and if an object is present, only one wavelength will be in focus on the object.

[0074] As a result, the system then relates color to height if it can detect which wavelength is in focus on the object. This detection is performed by a spectrometer. The preferred embodiment of a complete chromatic confocal system (FIG. **7**) includes a broad band, white source, a dispersive optical system, a spectrometer, and fiber coupler/splitter to connect the other parts and provide the confocal source and detector apertures. Many other configurations are possible.

[0075] The chromatic confocal sensor is also easily integrated with a microscope imaging system that shares the objective lens with the confocal sensor. The microscope provides an image of the object and provides an immediate reference for the location of the confocal measuring spot. For example, the measurement of wafer thickness after plating the wafer with solder bumps can be conducted using the microscope image to guide the measurement spot around the solder bumps. Another example is the measurement of pressure sensor diaphragms. These diaphragms are etched from the back side of the wafer to form a thin membrane of silicon for each die. The measurement of these diaphragms is impossible with the capacitance sensors because of their small dimensions. However, the chromatic confocal sensor with the integrated microscope easily locates the diaphragm and measures the thickness in localized spots. The integrated microscope is also important for the trench measurement application. For this application, the microscope is necessary to locate the trench so that it can be measured.

[0076] If the object is transparent, as is silicon in the NIR spectrum, a reflection from both the top and bottom of the object will be returned to the spectrometer. Since there is a difference in height from the top surface and the bottom surface of the wafer, the light reflected from each will be of a different wavelength. FIG. **5** shows the relative intensities of the reflections from the top and bottom of a glass slide in the visible spectrum. An analogous result is achieved when measuring silicon wafers in the near infrared spectrum. In general, chromatic confocal sensors are designed so that shorter wavelengths focus before longer wavelengths, although it is possible to design a sensor with the opposite relationship. In the preferred embodiment, the light focused on the top of the wafer has a shorter wavelength than the light focused at the bottom. When these reflections pass through the spectrometer, the spectrometer shows two wavelength peaks. The location of each peak indicates the location of each surface, and the difference in peaks indicates the thickness of the wafer.

[0077] The sensor mechanically scans the wafer in the transverse directions with a sample rate and data density specified by the user. Thousands, and potentially tens of thousands, of data points are thus acquired. The sensor has a spot size approximately 5 microns, giving surface and thickness measurements that are highly localized. As the sensor is moved around the wafer, the locations of the peaks will change as a function of the shape of the wafer surface, and the relative locations of the peaks will change as a function of thickness. Thus, the complete shape of the wafer is derived as well as localized thickness of the wafer.

[0078] There are no known chromatic confocal sensors designed to operate in the NIR. The design of a chromatic confocal sensor requires the use of dispersive materials to spread the wavelengths along the axis of focus. While many different materials are available to provide sufficient dispersion in the visible spectrum, the necessary dispersion in the NIR is more difficult to achieve. However, doublet lenses can be designed to provide axial dispersion as well as correcting for spherical aberration. One example uses S-TIH53 and N-SSK8 glasses, and another example uses S-TIH53 and N-SK4 glasses. Many other examples can be designed, including doubles using S-NPH1 in place of S-TIH53. To increase the amount of axial dispersion in a system, several such doublets can be used in a serial fashion. Another method to create the axial dispersive lens system is with the use of diffractive lenses in combination with refractive lenses.

[0079] Calibration is a critical issue for this invention. The measurement of the bottom surface is complicated by the effects of focusing through the wafer substrate. One effect is the addition of spherical aberration, which will effectively spread the focused spot on the bottom surface and reduce axial resolution.

[0080] Spherical aberration can be minimized through proper design of the focusing lens system. Another effect is the difference between physical length and optical path length when light propagates through a medium. The chromatic confocal sensor measures optical path length, whereas the quantity of interest is physical length, or thickness, of the wafer. The measured thickness is roughly equal to the physical thickness divided by the index of refraction of the wafer. However, the index of refraction varies with wavelength. The axial focus position of each wavelength in the silicon is approximately, $z(\lambda)=f(\lambda)n(\lambda)$, where f is the axial focus position in air, n is the index of refraction of silicon, and λ indicates that each of these quantities depend on wavelength.

[0081] FIG. **16** demonstrates how the index of refraction of a silicon medium affects measurement calibration. Because of the refraction at the first silicon surface, the chromatic confocal sensor actually measures to a point inside the wafer. Both the wafer thickness (seen in the left in FIG. **16**) and the trench measurement (seen on the right in FIG. **16**) are affected.

[0082] FIG. **16** further illustrates the measurement of a trench accounting for the refraction. The "raw" measurement is the apparent axial location of the confocal spots as measured by the calibrated spectrometer, but the "desired" measurement is the depth of the trench. A geometric optics analysis using Snell's Law shows that the "desired" measurement is simply equal to the "raw" measurement scaled by the index of refraction. Therefore, if the spectrometer response is calibrated to the confocal response in air, then the measurement of the trench depth in the substrate medium is simple. Alternatively, the spectrometer response can be directly calibrated using a step height gage fabricated from the same material as the substrate.

[0083] The chromatic axial focal shift that gives rise to the confocal signal is affected by the refractive index of the medium. A standard method for calibrating chromatic confocal systems in air is to use an angled gage block scanned with precise lateral motion. Such a calibration will provide a look up table between object height and wavelength peak. However, this calibration table would be incorrect in a medium other than air. The appropriate calibration table can be estimated by multiplying the object heights by the index of refraction. However, the index variation with wavelength must be accounted for. Alternatively, a calibration gage can be fabricated in silicon so that a direct calibration can be made.

[0084] The illustrations and examples provided herein are for explanatory purposes and are not intended to limit the scope of the appended claims. This disclosure is to be considered an exemplification of the principles of the invention and is not intended to limit the spirit and scope of the invention and/or claims of the embodiment illustrated. Those skilled in the art will make modifications to the invention for particular applications of the invention.

What is claimed is:

1. A method for measuring trench depth on a wafer comprising

microscopically locating said trench on said wafer, said wafer having a front surface and a back surface such that said trench is on said front surface;

positioning a non-contact optical instrument facing said back surface so that said trench is effectively a bump on said second surface from said non-contact optical instrument, said non-contact optical instrument utilizing a light source such that said wafer is transparent and said non-contact optical instrument receives reflected light from said back surface and said front surface of said wafer such that said front surface indicates the interior of said trench;

taking the measurement of the height of said bump using a light source set in a wavelength range wherein said wafer is transparent;

calibration of said bump height through a conversion of said measured height differences between said top surface and said bottom surface thereby determining the shape and contour of said wafer at the site of said trench.

2. A method according to claim **1** wherein said wafer is composed of one of the following group: silicon, GaAs, GaAIAs, InP, SiC, SiO_2.

3. A method according to claim **1** wherein said light source is in the near infrared region, having a wavelength range of 900 nm to 1700 nm.

4. A method according to claim **1** wherein said non-contact optical instrument is a chromatic confocal sensor.

5. A method according to claim **4** wherein said chromatic confocal sensor utilizes a calibration means that converts said collected data corresponding to said wavelengths of said reflected light from said top surface and said bottom surface of said wafer and the corresponding height differences into a measured thickness that determines the depth of said trench or said thickness of said localized area on said wafer.

6. A method according to claim **1** wherein said non-contact optical instrument uses white light interferometry.

7. A method according to claim **1** wherein said non-contact optical instrument uses phase shift interferometry.

8. A method according to claim **1** wherein said non-contact optical instrument uses scanning confocal microscopy.

9. A method according to claim **1** wherein said non-contact optical instrument uses laser triangulation.

10. A method according to claim **1** wherein said optical instrument mechanically scans said wafer in transverse directions at a pre-specified sample rate and density.

11. A method for measuring localized thin wafer thickness comprising

microscopically locating said localized thickness area on said wafer, said wafer having a front surface and a back surface;

positioning a non-contact optical instrument on one side of said wafer to receive reflected light from said top surface and said bottom surface simultaneously;

taking the measurement of the thickness of said wafer using a light source set in a wavelength range wherein said wafer is transparent;

calibration of said localized wafer thickness through a conversion of said measured height differences between said top surface and said bottom surface thereby determining the localized thickness of said wafer.

12. A method according to claim **11** wherein said wafer is composed of one of the following group: silicon, GaAs, GaAIAs, InP, SiC, SiO_2.

13. A method according to claim **11** wherein said light source is in the near infrared region, having a wavelength range of 900 nm to 1700 nm.

14. A method according to claim **11** wherein said non-contact optical instrument is chromatic confocal sensor.

15. A method according to claim **14** wherein said chromatic confocal sensor utilizes a calibration means that converts said collected data corresponding to said wavelengths of said reflected light from said top surface and said bottom surface of said wafer and the corresponding height differences into a measured thickness that determines the depth of said trench or said thickness of said localized area on said wafer.

16. A method according to claim **11** wherein said non-contact optical instrument uses white light interferometry.

17. A method according to claim **11** wherein said non-contact optical instrument uses phase shift interferometry.

18. A method according to claim **11** wherein said non-contact optical instrument uses scanning confocal microscopy.

19. A method according to claim **11** wherein said non-contact optical instrument uses laser triangulation.

20. A method according to claim **11** wherein said optical instrument mechanically scans said wafer in transverse directions at a pre-specified sample rate and density.

21. An apparatus for measuring trench depth on a wafer or localized thickness of said wafer, said wafer having a top side and a bottom side, said apparatus comprising

a non-contact optical height measurement instrument;

a securing means located substantially beneath said non-contact optical height instrument for positioning of said wafer;

a light source set in a wavelength range wherein said wafer is transparent;

said non-contact optical instrument being positioned on one side of said wafer to receive reflected light from said top surface and said bottom surface simultaneously;

data collection means that receives data from said non-optical height measurement instrument.

22. An apparatus according to claim **21** wherein said wafer is composed of one of the following group: silicon, GaAs, GaAIAs, InP, SiC, SiO_2.

23. An apparatus according to claim **21** wherein said light source is in the near infrared region, having a wavelength range of 900 nm to 1700 nm.

24. An apparatus according to claim **21** wherein said non-contact optical instrument is a chromatic confocal sensor.

25. An apparatus according to claim **24** wherein said chromatic confocal sensor utilizes a calibration means that converts said collected data corresponding to said wavelengths of said reflected light from said top surface and said bottom surface of said wafer and the corresponding height differences into a measured thickness that determines the depth of said trench or said thickness of said localized area on said wafer.

26. An apparatus according to claim **21** wherein said non-contact optical instrument uses white light interferometry.

27. An apparatus according to claim **21** wherein said non-contact optical instrument uses phase shift interferometry.

28. An apparatus according to claim **21** wherein said non-contact optical instrument uses scanning confocal microscopy.

29. An apparatus according to claim **21** wherein said non-contact optical instrument uses laser triangulation.

30. A method according to claim **21** wherein said optical instrument mechanically scans said wafer in transverse directions at a pre-specified sample rate and density.

31. A method of measuring the thickness, flatness and localized shape of a thin wafer, said wafer having a top side and a bottom side, said method comprising

calibrating the distance of said wafer from a first sensor and a second sensor, said distance calibration further comprising

placing a gage block of a known thickness and containing parallel surfaces between said first and second sensors in a suitable holder;

adjusting said first and second sensors in the Z plane such that the surface being sensed is placed at the middle of the sensor measurement range;

measuring the localized thickness of said wafer, said measurement further comprising

placement of said wafer in a suitable holder allowing said first and second sensors to receive responses from both sides of said wafer;

moving said wafer in said suitable holder through a predetermined number of locations either individually at each of said locations or continuously;

recording the height values at each of said locations or continuously;

converting said height values to thickness values at each of said locations or continuously;

computing the shape and shape variations of said wafer through a mathematical calculation;

displaying said mathematical calculations of shape and shape variations through a displaying means.

32. A method according to claim **31** wherein a further calibration step is added, said calibration step further comprising

calibrating said sensor height, said sensor height calibration further comprising first placement of an angle gage block of known angle between said first and second sensors in a suitable holder with the flat surface of said angle gage block being perpendicular to said first sensor, giving a surface of known angle to said first sensor;

rotating said angle gage block 180 degrees, placing the slope of said angle gage block in the opposite direction from said first placement with said angle gage block being perpendicular to said first sensor, giving a surface of known angle to said first sensor;

converting said collected height sensor calibration mathematically and thereby calculating the tilt of said angle block;

turning said angle gage block to present said angle gage block to said second sensor, repeating steps as applied to said first sensor.

33. A method according to claim **31** wherein said sensors are chromatic confocal.

34. An apparatus for measuring the thickness, flatness and localized shape of a thin wafer, said wafer having a top side and a bottom side, said apparatus comprising

a first stage for calibrating the distance of said wafer from a first sensor and a second sensor, said distance calibration further comprising

placing a gage block of a known thickness and containing parallel surfaces between said first and second sensors in a suitable holder;

adjusting said first and second sensors in the Z plane such that the surface being sensed is placed at the middle of the sensor measurement range;

a second stage for measuring the localized thickness of said wafer, said measurement further comprising

placement of said wafer in a suitable holder allowing said first and second sensors to receive responses from both sides of said wafer;

moving said wafer in said suitable holder through a predetermined number of locations either individually at each of said locations or continuously;

recording the height values at each of said locations or continuously;

converting said height values to thickness values at each of said locations or continuously;

computing the shape and shape variations of said wafer through a mathematical calculation;

displaying said mathematical calculations of shape and shape variations through a displaying means.

35. An apparatus according to claim **34** wherein there is a third stage for calibrating said sensor height, said sensor height calibration further comprising

a second stage for calibrating said sensor height, said sensor height calibration further comprising

first placement of an angle gage block of known angle between said first and second sensors in a suitable holder with the flat surface of said angle gage block being perpendicular to said first sensor, giving a surface of known angle to said first sensor;

rotating said angle gage block 180 degrees, placing the slope of said angle gage block in the opposite direction from said first placement with said angle gage block being perpendicular to said first sensor, giving a surface of known angle to said first sensor;

converting said collected height sensor calibration mathematically and thereby calculating the tilt of said angle block;

turning said angle gage block to present said angle gage block to said second sensor, repeating steps as applied to said first sensor;

36. An apparatus according to claim **34** wherein said sensor is chromatic confocal.

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