Paper

Through-hole Interconnections Formed by Optical Excitation Electropolishing Method

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Through-hole interconnections were fabricated by refilling the through-holes, formed by the optical excitation electropolishing method[1] (OEEM), with indium by the molten metal suction method. In the specimen used for this experiment, through-holes were formed with a density of 11.6 holes/mm^2 and an aspect ratio of 52. On the wall surfaces of the through-holes, a 500 nm thick oxide film was formed by pyrogenic oxidation to provide a dielectric film. The dielectric breakdown voltage of this film was over 300 V, and the stray capacity was less than 80 pF/hole. Indium sheets of 4N (99.99 %) purity were placed on the specimen surface and melted at 350 ℃ by a halogen lamp、and the molten indium was sucked into the through-holes in a vacuum of 0.05 Torr. By this open-type method of sucking molten metal in the air, the whole process could be completed in less than 5 minutes and the through-holes less than 50 aspect ratio could be refilled with indium with an efficiency higher than 90%. To use the refilled holes as through-hole interconnections, a pole or mushroom type solder (Sn: Pb = 6.4) bump was formed on the top of the holes by electroplating. The obtained through-hole interconnections had a resistivity of less than 100 mΩ and were excellent in gastightness with no leakage exceeding the detection limit of Radiflo leak test (1.0×10^{-10} Pa · m^3/sec). Based on the result, it was confirmed that through-hole interconnections having an aspect ratio of 50 and a superior gastightness could be formed, suggesting success in producing self-package type three-dimensional devices.

KEYWORD: optical excitation electropolishing, molten metal suction method, through-hole interconnection, three-dimensional device

1. Introduction

The sensor technology is advancing toward miniaturization and intellectualization. In terms of miniaturization, the package in which sensor elements are connected together on a plane constitutes a great obstacle to the reduction in size and weight of sensors. As to intellectualization, integrated sensors having a sensor and a circuit in the same element are available in the market. However, the integrated sensors in which circuits are arranged on the same plane as sensors are disadvantageous in that the fabrication process becomes complicated, resulting in lower production efficiency. Moreover, sensors are often contaminated during the process, causing unfavorable effects such as deterioration in reliability of integrated circuit elements. As a new approach for eliminating such drawbacks of the integrated sensors, the development of a flip-chip type (self-package type) device, in which sensors and integrated circuits are formed into a single block by connecting them in the Z-direction in a three-dimensional system, has been drawing attention[2][3]. In the case of this flip-chip type device, sensor elements and integrated circuit elements are made in separate processes, and are joined with each other in the Z-direction with a through-hole interconnection element between them. At the same time, the electrodes of different functional elements are connected in the Z-direction as well. In the through-hole interconnection element, it is possible to cross wires and interchange electrodes. Aiming at higher integration, attempts are being made to develop a "double IC" method of arranging sensors and circuits on both surfaces of Si wafers and a "wafer-level three-dimensional integrated element" method of stacking sensors and circuits in the Z-direction into a single block[4]. This requires wires (interconnections) which connect the sensors and circuits on both wafer surfaces.
To accomplish the through-hole interconnections which connect the both wafer surfaces, it is necessary to develop a process of forming through-holes with a size of several μm in the Si wafer as well as a process of refilling the through-holes with metal.

This paper introduces the process of forming through-holes with a high aspect ratio by the OEEM, the process of refilling the through-holes with indium by the open type molten metal suction method, and the evaluation results of the obtained through-hole interconnections.

2. Experimental Procedure

In this experiment, N-type Si wafers grown by the MCZ method were used. Both surfaces of the wafer were polished to reduce the wafer thickness to 525 μm and were mirror-finished with Miller index (100). The resistivity of the wafer was 8.0-12.0 Ω · cm. The through-hole forming process is shown in Figure 1. The anode of the instrument used in the OEEM was a Cu plate. In order to decrease the contact resistance between the Cu plate and Si wafer, highly-doped phosphorus was diffused over the bottom surface of the Si wafer to form an electrode layer of 2.2 μm thickness and a surface dopant density of 2.2×10^{20} atoms/cm^3.

A thin Si_3N_4 film 120 nm thick was deposited on the surface of the Si wafer except V- pit areas to protect it from the electropolishing reaction, and then the surface was coated with a double metal film of Cr (50 nm) and Pt (150 nm) by sputtering so that the electric current could be uniform throughout the through-hole forming process. After that, the metal film in the areas in which to form through-holes were patterned by using the lift-off method, and the Si_3N_4 film was etched with hot phosphoric acid (H_3PO_4:150 ℃) with the patterned metal film as a mask. Using the "window" thus formed as a mask, the Si wafer was etched by anisotropic etching with a 43 wt% KOH solution to form V-pits (10 μm square and 6.9 μm deep) therein. The pretreated 4-inch Si wafer was cut into 25 mm square pieces to provide specimens for forming deep-capillaries.

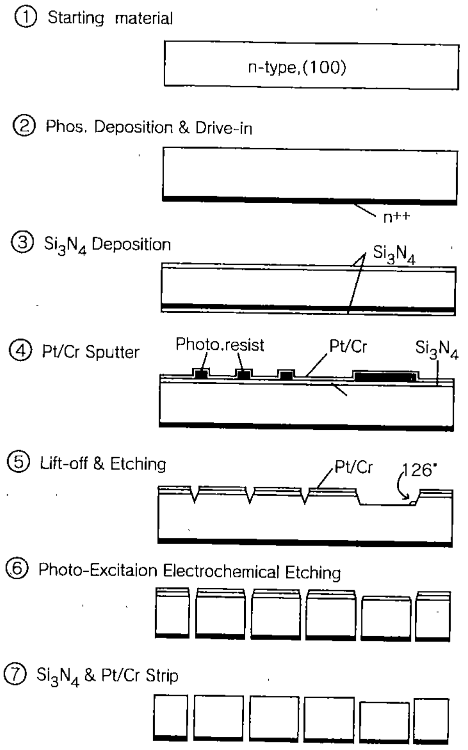


Fig. 1 Through-hole forming process using OEEM

Figure 2 shows the setup of OEEM instrument. A high-pressure mercury lamp (Ushio: USH-205DP) was used as the light source. Parallel rays of light were obtained using the combination of a concave mirror, lenses and other optical apparatus. This light was led through an bandpass filter in the lower part of the instrument to illuminate uniformly an area less than 30 mm square on the bottom surface of the Si wafer at right angles. The wavelength range of the bandpass filter used in this experiment is 380-750 nm.

A 2.5 wt% HF solution was used as the electrolyte. The temperature of the electrolyte (5 lit.) was controlled at 45±1.0 ℃ in a thermostat (Taitek:CH-400B), and the electrolyte was circulated in the reaction tank of 300 cm^3 capacity at a flow rate of 1.0 lit./min. Thus, the electrolyte in the tank was replaced at least three times per minute. The level of the electrolyte was kept constant at 45 mm. In addition, the distance between the light source and Si wafer was fixed at 460 mm and the distance between the anode and cathode was fixed at 25 mm. A galvanostat/potentiostat (Toho Technical Research: Model 2100) was used as the power source, and the electric charge passed through the Si wafer was measured using a coulombmeter (Model 3320-10A).

The standard conditions for forming through-holes by the OEEM were as follows:

- Electrolyte: 2.5 wt% HF solution

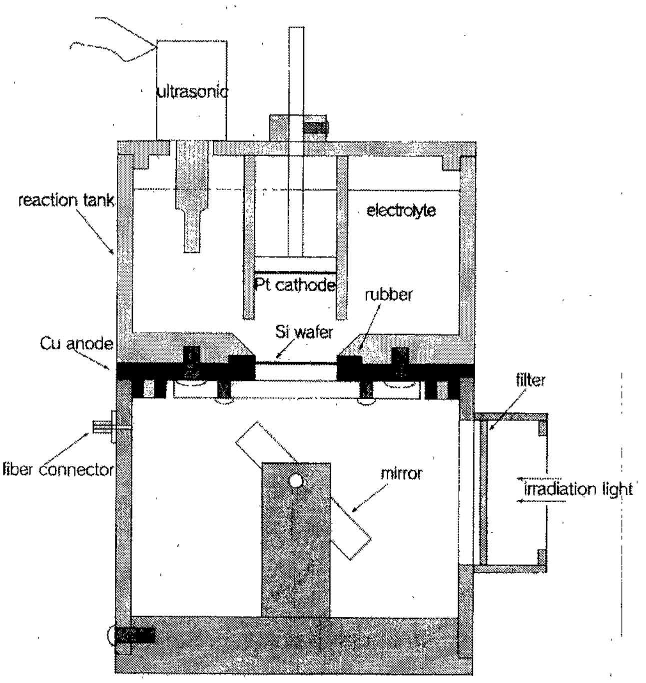


Fig. 2 Cross section of OEEM instrument

- Surfactant: 10 wt% C_2H_5OH
- Current density: 12 mA/cm^2
- Temperature of electrolyte: 45 ℃
- Electric charge passed through Si wafer: 180 C
- Light source: high pressure Hg lamp
- Wavelength range: 380-750 nm
- Intensity of irradiation light: 100 mW/cm^2

Figure 3 illustrates the instrument used in the molten metal suction method. In the open-type molten metal (indium) suction method, a specimen with through-holes was placed on a quartz filter (0.7 mmΦ) and held on the instrument in a vacuum of 0.1 Torr. On the surface of the specimen, 4N (99.99%) pure indium sheets about 5.0 g in weight were placed. Then, the indium sheets were melted by the halogen lamp. Three minutes after, the molten indium was sucked into the through-holes in a vacuum of 0.05 Torr and held for one minute. Two minutes after turning off the vacuum pump, the excess molten metal was removed by a squeegee. Using the open-type molten metal suction method as mentioned above, the through-holes were refilled with indium to form through-hole interconnections.

3. Experimental Results and Discussion

3-1. Fabrication of Through-holes by OEEM

The study on the electropolishing of Si wafers with HF solution started about 50 years ago. Since then, many researchers have presented their papers(5)(6). In 1990, Canham(7) reported that porous silicon emits visible red light even at room temperature owing to a quantum effect when it is irradiated with Ar laser. This contributed to enlivening the research activities in the field concerned. In order to confirm this phenomenon, the author also carried out an experiment using a P-type (100) Si wafer of 1-2 Ω·cm resistivity. Figure 4 shows the relation between the current density and the concentration of electrolyte (HF).

In this figure, there are three types of regions: 1) region of dark brown porous Si layers (marked ●) having a mechanical strength enough to emit visible light; 2) region of fragile porous Si layers (marked ○) that are easily broken into grains like sand at a touch; and 3) electropolishing region (marked ■) where no porous Si layer is formed.

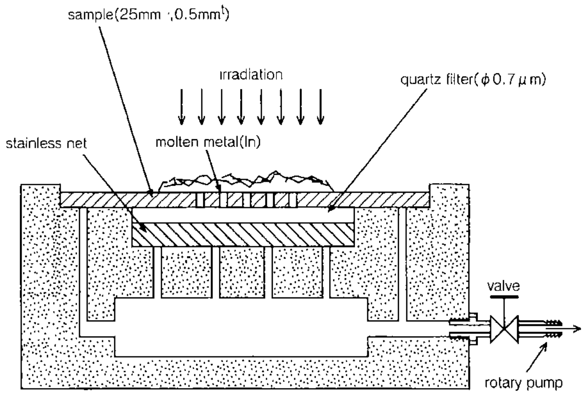


Fig. 3 Cross section of molten suction instrument

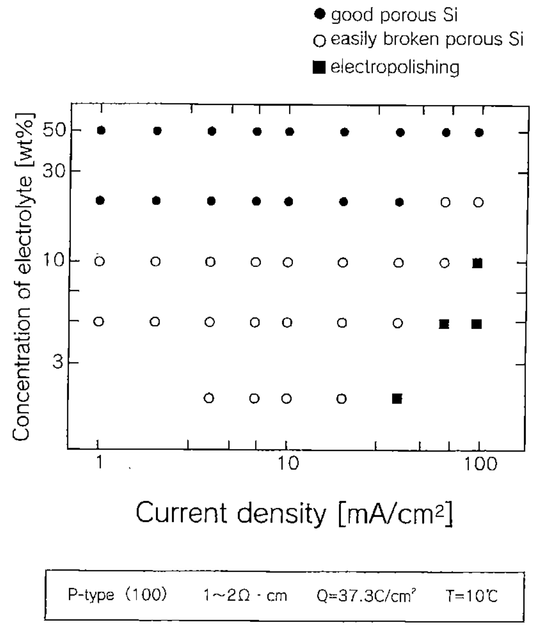


Fig. 4 Relation between current density and concentration of electrolyte

An attempt was made to form through-holes by electropolishing only the specified areas in the electropolishing region. The chemical equations suggested by Unagami et al.(8) for the electropolishing process indicates that positive holes play an important role in the process. In order to control the positive holes, an N-type (100) Si wafer was selected as the starting material and the generation of positive holes was controlled by irradiating the bottom surface of the wafer with an appropriate quantity of light. And through-holes were formed by electropolishing only the specified areas in which positive hole is converged.

To specify the areas in which through-hole is formed, V-pits were formed by anisotropic etching on the surface of the Si wafer.

The positive holes as minority carriers in the Si wafer are excited by irradiating the bottom surface of the wafer with the light of the high pressure mercury lamp. A DC voltage of about 1.0 V is applied to between the Si wafer (anode) and Pt plate (cathode) shown in Figure 2, so the positive holes move toward the surface of the Si wafer. If V-pits having a tip angle of 72 degrees exist on the wafer surface, the positive holes converge on the V-pit tips. As the electrolyte is in contact only with the V-pit tips on which the positive holes have converged, the electropolishing reaction occurs there only. Through-holes were finally formed with an etching rate of 1.0 μm/min. Photograph 1 shows the cross section of the through-holes. The size of the through-hole was then determined from the length of one side of the V-pit.

In order to decide the concentration of electrolyte, the relation between the amount of dissolved silicon and the electrolyte concentration was investigated, assuming the following as the OEEM conditions: the current density is 7 mA/cm^2, the charge passed is 100C, and the electrolyte temperature is 50 ℃. The result is given in Figure 5. The amount of dissolved silicon was calculated from the weight measurements of the Si wafer before and after the electropolishing process.

As pointed out by T. Unagami(8) et al, silicon is dissolved in water in the form of H_2SiF_6, and the amount of HF in the electrolyte plays an important part. As seen from Figure 5, the amount of dissolved silicon exhibits a sudden decrease when the concentration of electrolyte (HF) is less than 2.5 wt%. This indicates that the amount of HF was insufficient for the chemical reaction. When the HF concentration is too high, micro-pores are formed, but macro-pores in sizes over 1.0 μm square cannot be formed because silicon is dissolved in the form of porous silicon as shown in Figure 4. That is, the electropolishing reaction is more apt to occur with lower HF concentration. In addition, the amount of dissolved silicon approaches saturation, beginning with the HF concentration of 2.5 wt%. Taking these into account, the HF concentration range in which macro-pores can be formed by the OEEM was confirmed by the experiment to be from 2.5 to 5.0 wt%.

Considering that optical excitation electropolishing is a chemical reaction which corrodes the Si wafer for hole forming in it, the hole forming rate varies with the electrolyte temperature. Therefore, the relation between the electrolyte temperature and the increment in hole depth per coulomb of electric charge passed through the Si wafer, i.e., the relation between temperature and hole forming efficiency, was investigated. The result is given in Figure 6. From the figure, it can be seen that the through-hole forming efficiency is higher with higher electrolyte temperature. It was also found by another experiment that the activation energy of optical excitation electropolishing is 0.44 eV, which is nearly equal to the activation energy (0.48 eV) of anisotropic etching of silicon with ethylenediamine (34.4 wt%)(9). This indicates that the through-hole formation by optical excitation electropolishing is also a chemical reaction.

By investigating the voltage-current characteristic in terms of time in the process of forming through-holes by the OEEM, two different modes were observed as shown in

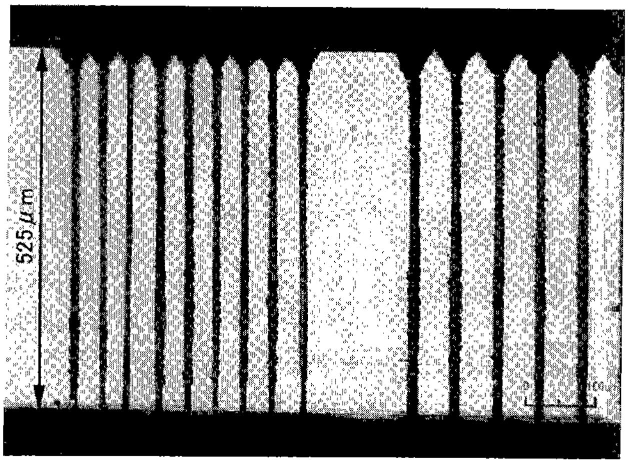


Photo. 1 Cross section of through-holes formed by OEEM

Through-holes 10 μm square with aspect ratio of 52.5.

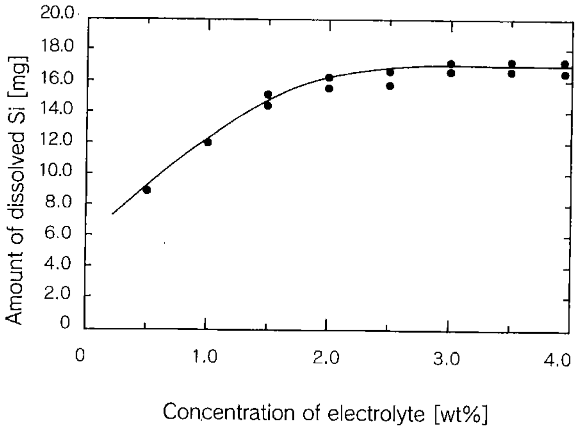


Fig. 5 Maximum amount of dissolved Si Vs. electrolyte concentration

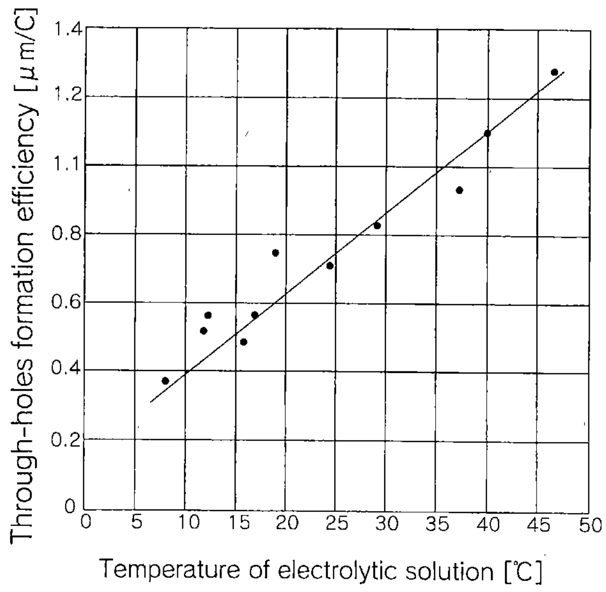


Fig. 6 Temperature dependency of the through-hole formation efficiency by using OEEM

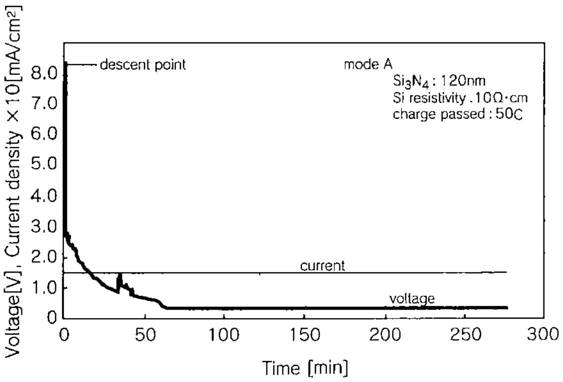


Fig. 7 The voltage/current against time in the case of forming deep capillaries in Mode A

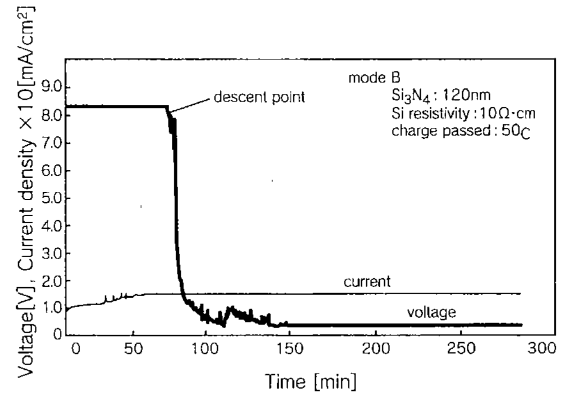
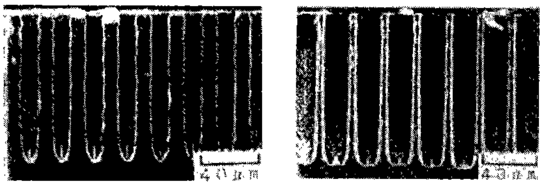


Fig. 8 The voltage/current against time in the case of forming deep capillaries in Mode B



Mode A Mode B

Photo. 2 Cross section of the specimens in Mode A and Mode B

Figures 7 and 8. The cross sections of deep capillaries in the respective modes are shown in Photograph 2. As apparent from the photograph, there are two types of modes: Mode A in which only the reaction progressing in the depth direction is dominant with the hole wall surface kept smooth, and Mode B in which the reaction progressing in the direction in which to increase the hole size is dominant. The characteristic feature of the reaction seen in Figure 8 is that the voltage curve remains constant at about 8.3V during the period from immediately after the start of the reaction to the descent point. This is because the voltage measuring instrument has a limiting circuit which prevents the voltage exceeding 8.3V. The relation between the intensity of irradiation light and the initial

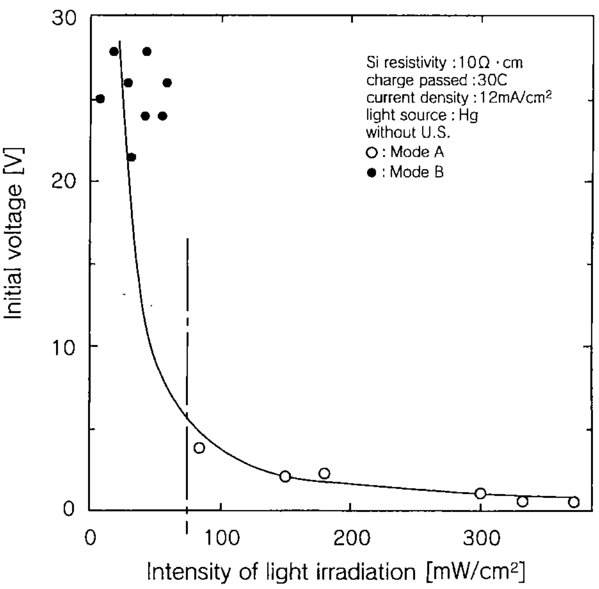


Fig. 9 Relation between intensity of irradiation light and initial voltage

Initial voltage value becomes high and unstable when the intensity of irradiation light is smaller than 80 mW/cm^2

voltage measured immediately after the start of the reaction by the voltage measuring instrument without the limiting circuit is shown in Figure 9. The initial voltage is high when the intensity of irradiation light is low. This indicates that the hole current is very small because very few positive holes are excited in the Si wafer. That is, as this experiment uses the constant current method, the voltage increases to maintain the constant current because of very small hole current.

That is, the initial voltage is divided into a high voltage (Mode B) and a low voltage(Mode A) regions at the borderline shown by the alternate long and short dash line indicating the intensity of irradiation light, 80 mW/cm^2, in Figure 9. If the Si wafer is not irradiated with light, minority carriers are not excited in the wafer and no current flows. Therefore, the reaction of forming deep capillaries does not occur.

The relation between the hole depth and current density given in Figure 10 shows that the data of Mode A are on a straight line, but those of Mode B are scattered. At the current density of 18 mA/cm^2, the number of specimens deviating from the straight line of Mode A is 12, of which three are Mode A specimens and nine are Mode B specimens. Surface and sectional photographs of all the specimens were taken to investigate the differences between them. Consequently, it was found that the reaction left a trace about 1.00 μm wide on the outermost periphery of the region where the V-pit patterns gathered

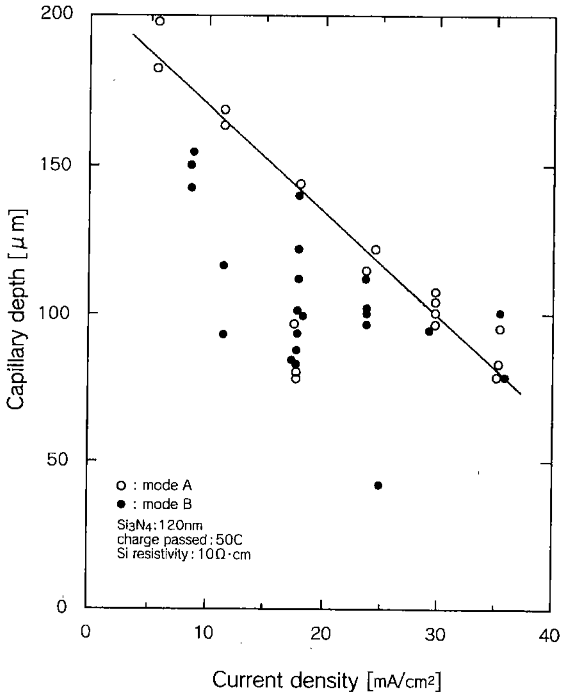


Fig. 10 Relation between the capillary depth and the current density

The intensity of irradiation light is over 80 mW/cm^2 for Mode A and 80 mW/cm^2 or less for Mode B.

together as shown in Figure 11. This is because the entire region of gathered V-pit patterns are etched and concaved. This suggests that when a high voltage Mode B is applied to the Si wafer, the positive holes converge not only on the V-pit tip (three-dimensional element) at a depth of 6.9 μm from the Si surface but also on the acute-angled portion (two-dimensional element) of the pattern formed on the Si surface, and overall electropolishing starts from this portion.

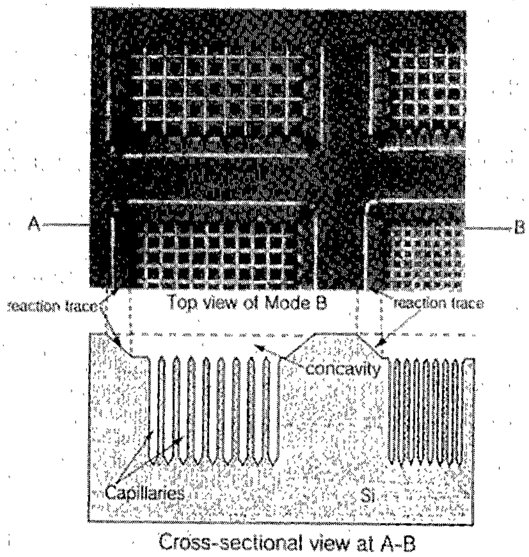


Fig. 11 Cross section and top view of Mode B device

Mode B has the concavity which was fabricated by the peripheral effect

That is, the positive holes not only converge inside the Si wafer (three-dimensional element) on the V-pit tip but also converge on the surface of the Si wafer because the field distribution becomes nonuniform, depending on the arrangement and distribution density (two-dimensional elements) of V-pit patterns. Particularly when a high voltage is applied to the corners and the outermost periphery of the region where the V-pit patterns gather together, the electropolishing reaction occurs even on the surface. Therefore, the entire pattern region forms a concave as shown in the top view of Figure 11. This phenomenon is called "peripheral effect." And the current used for etching other spots than those in which to form holes is named "ineffective current."

From these photographs, the depth of the formed concave and the area of parts other than the V-pits were measured, and the amount of dissolved silicon from the concave was calculated. Next, to what a hole depth (d1) this amount of dissolved silicon corresponds was calculated, and the calculated value was added to the hole depth (d) in the specimens (d+d1). As a result of this calculation, all depth data of the 12 specimens were found to be within 140±8 μ m. That is, the 12 scattered depth data could be put on the straight line of Mode A. The scattered depth data of Mode B specimens obtained at other current densities could also be put on the straight line of Mode A. From this fact, it can be seen that the original OEEM reaction is Mode A. Of the 12 specimens, three were judged to be Mode A specimens. In all of the three specimens, however, the depth of concave was no more than 1/4 that in the Mode B specimens, but the hole size was two times as large as the design value. As a result of the same calculation as that for Mode B, the depth data of these specimens were also found to be within 140±8 μ m and could be put on the straight line of Mode A. However, .the reason why the depth data of Mode A specimens were scattered is not due to decreased intensity of light, but seems to be that the specimens were in poor contact with the electrolyte due to contamination of openings or the presence of gas bubbles. The phenomenon of the three specimens should also be considered as a peripheral effect.

Here, the process in which Mode B specimens are formed is considered. In the initial stages of hole forming by the OEEM reaction, when (1) the Si surface of the V-pit is in poor contact with the electrolyte due to contamination resulting from insufficient cleaning or the presence of the remainder of naturally oxidized film or gas bubbles, or (2) the intensity of the light irradiating the bottom surface of specimen decreases to less than 80 mW/cm^2 due to degradation of the light source, resulting in insufficient number of positive holes required, the initial voltage becomes higher because the OEEM uses the constant current method. In addition, when (3) the V-pits are unevenly arranged, or (4) the four corners of V-pit patterns have sharp edges, the current distribution becomes nonuniform. Therefore, the OEEM reaction occurs even in a part other than the V-pit. If the current flows unevenly though the reaction of Mode A is proceeding, a current higher than the setting will partly flow, causing the hole size to be enlarged, and the hole depth will decrease where less current flows. These problems could be solved by taking the three following measures:

(a) Improve the pretreating process to ensure better contact with the electrolyte.

(b) Increase the intensity of irradiation light.

(c) Improve the mask pattern.

The reason why the initial voltage drops with time is considered as follows. As the reaction progresses with time, the reaction point displaces from the wafer surface to the deep part. Therefore, the moving distance of the positive holes becomes shorter, decreasing electric resistance. In addition, as the electrolyte is led to the tank by the circulation method, the bubbles can be removed, resulting in better contact between the Si wafer and electrolyte and hence in smaller electric resistance.

When fabricating through-holes by the OEEM, it is very important to control the number of positive holes excited by irradiation with light. As the hole forming reaction is divided into Mode A and Mode B at the borderline shown by the alternate short and long dash line (80 mW/cm^2) in Figure 9, the number of positive holes at this intensity of irradiation light is the threshold. Therefore, the then number of positive holes was determined in the following ways. That is, the number of positive holes generated by irradiating the bottom surface of the Si wafer was calculated using the software (PC1D) developed by the Photovoltaics Special Research Center at the University of New South Wales. PC1D calculates the photogeneration profiles as a function of wavelength by assuming a different exponential spacial dependence for each wavelength. The optical absorption coefficients can be generated using the internal theoretical model for photon absorption. The obtained result is shown in Figure 12. The diffusion length used in this calculation was calculated as follows. First, the hole lifetime was measured at room temperature by the photoconductive attenuation method. And the diffusion length L_H was calculated by the equation$^{(10)}$:

$$L_H=\sqrt{(KT/q)\mu\tau}$$

where μ is the hole mobility and τ is the hole lifetime.

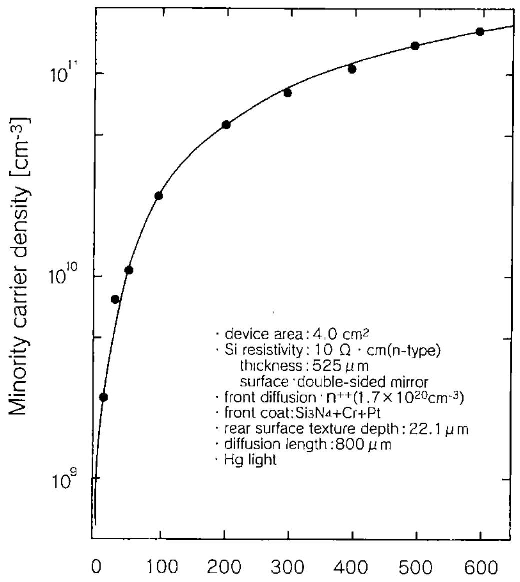


Fig. 12 Irradiation intensity dependence of minority carrier (positive hole) density

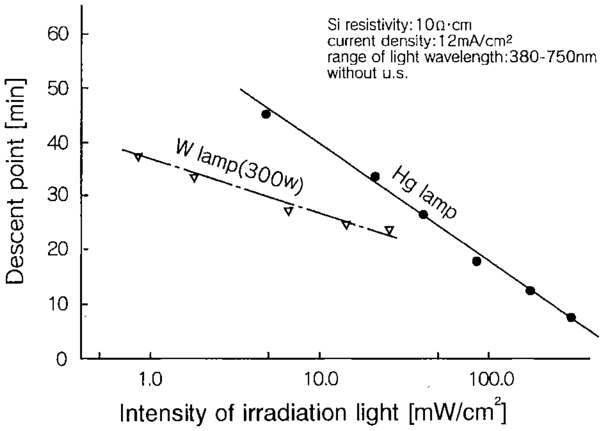


Fig. 13 Relation between the descent point and the density of irradiation light from two type light sources

With a wafer of 10 Ω·cm resistivity, the calculated diffusion length was about 800 μm, which was greater than the thickness of the wafer.

By controlling the irradiation light so as to excite more positive holes than the threshold number when forming through-holes in a well pretreated Si wafer, it become possible to obtain through-holes in the Mode A reaction.

Figure 13 shows the relation between the descent point and the intensity of irradiation light. With a 300W W-lamp, the descent point will not appear within 15 minutes. Therefore, the W-lamp cannot be used as the light source for forming deep capillaries such as through-holes. Three kinds of W-lamps available at ordinary electric appliances stores were also investigated, but neither of them showed a decent point within 15 minutes. In addition, judging from the gentle slope of the straight line of the W-lamp shown in Figure 13, it is difficult to obtain an intensity of irradiation light over 100 mW/cm^2. Even if a W-lamp of such a high intensity is available, it will hardly be used with such a small system as is employed in this experiment because it is too large in size and amount of heat dissipation. W-lamps comprise most of the long wavelength region of 750 to 1000 nm, while Hg-lamps comprise most of the short wavelength region of 370 to 750 nm. In the OEEM REACTION, therefore, an Hg-lamp is better than a W-lamp of the same power because the former is higher than the latter in the intensity of irradiation light falling on the Si wafer after being passed through the bandpass filter in the OEEM. For this reason, it is presumed that the W-lamp was insufficient in the quantity of light in the wavelength region of 370 to 750 nm used in this experiment.

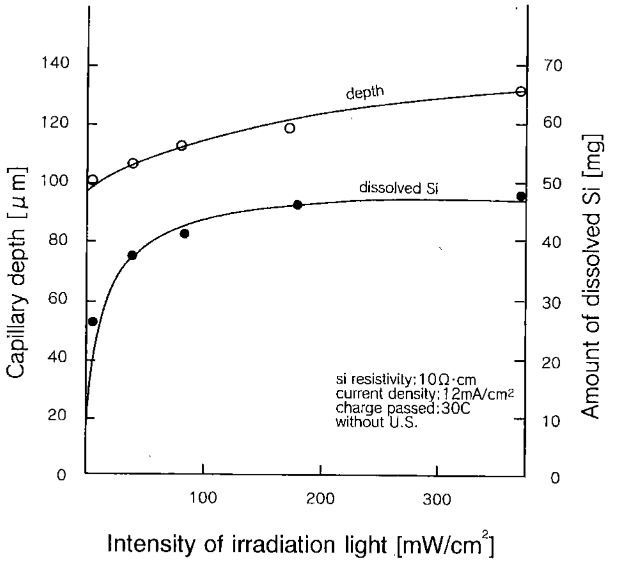


Fig. 14 The capillary depth and the amount of dissolved Si are plotted against the intensity of irradiation light under the standard conditions

According to the feasibility study, the light in the long wavelength region of 750 to 1000 nm penetrates to a great depth, so the positive holes collide against the inner surface of the Si wafer, change the moving direction and are scattered. Therefore, it becomes difficult to converge positive holes at the specified spots, so the hole size tends to increase widthwise. That is, the reaction becomes similar to the Mode B reaction. For this reason, the light in the short wavelength region of 370 to 750 nm is advantageous in forming through-holes.

Figure 14 shows a plot of the hole depth and the amount of dissolved silicon against the intensity of irradiation light in the Mode A reaction when forming through-holes in the Si wafer under the standard conditions.

It is noted that the values in Mode B are used at the light intensities less than 80 mW/cm^2 in the figure. The charge passed through the Si wafer is kept constant at 30 C with no ultrasonic waves applied. When the intensity of irradiation light is higher than 200 mW/cm^2, the amount of dissolved silicon remains constant at about 47 mg. But the hole depth slightly increases with increasing intensity of irradiation light as the chemical reaction in Mode A is proceeding. When the intensity of irradiation light is lower than 100 mW/cm^2, the chemical reaction by the OEEM becomes insufficient as the number of excited positive holes is small. The amount of dissolved silicon suddenly decreases with decreasing intensity of light as shown in Figure 14. Therefore, the size of through-holes made in the areas in the region of low intensities of light becomes smaller than the design value.

Considering the effect of ultrasonic wave from the angle of through-hole formation, the etching rate in the direction of the hole depth approaches saturation when the electric charge passed through the Si wafer exceeds 300 C as shown in Figure 15. This is because the reaction products become unable to be removed from the reaction point and therefore the reaction solution cannot be replaced. This problem was solved by utilizing the ultrasonic wave to accelerate chemical reactions. The ultrasonic wave has the following effects:

(1) Crushing bubbles: cavitation effect

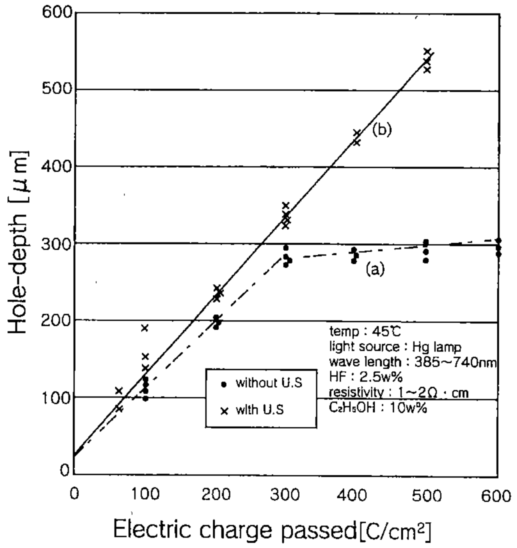


Fig. 15 Relation between electric charge passed and hole depth

(a): The hole-depth became saturated at around 300C.

(b): The hole-depth with supplementary energy of ultrasonic (U.S) waves increased linearly with the electric charge passed.

(2) Forming rectilinear waves on and in the liquid by vibration energy to convey fresh electrolyte to the reaction points in deep capillaries: capillary effect

(3) Stirring action

Therefore, the ultrasonic wave accelerates reactions physically and chemically. The ultrasonic oscillator used in this experiment was an ultrasonic homogenizer (Ultrasonic Engineering: Model USH-20Z20S) (resonance frequency = 21 kHz; power = 10 W; amplitude = 24 μm). The oscillator was set 5.0 cm apart from the specimen in the horizontal direction and off to the upper side at an angle of 30 degrees to the plane perpendicular to the specimen surface. Photograph 1 shows the cross section of the formed through-holes. The through-holes are 10 μm square and 525 μm deep, so the aspect ratio is 52.5 .

3-2. Refilling Through-holes with Metal

Not a few papers on through-hole interconnections have already been published(11)(12). In any of them, however, a description is made of only such a process that deposits metal onto the wide wall surface of the through-hole or plating the surface with metal because the purpose of forming through-hole interconnections is to make electrical conduction only. And the need for better gas tightness and higher density of interconnections is quite neglected there.

Moreover, the hole forming methods proposed there are limited to making holes by simultaneous anisotropic etching or dry etching of both surfaces, using an unsuitable procedure and spending much time, and no discussion is made of higher density, aspect ratio, cost performance, etc.

The purpose of this experiment was to form through-hole interconnections excellent in gas tightness with higher aspect ratio and higher density at arbitrary positions of different layers (elements) having different functions in order to ensure different operating conditions in the different layers of a three-dimensional device. As shown in Figure 16, the through-hole interconnection (THIC) device formed by the experiment is 2.5 mm by 2.5 mm by 0.52 mm in outside dimensions and has a total of 73 through-hole interconnections. The density of interconnections is 11.6 holes/mm^2 and the size 10 μm, so the aspect ratio is 52. These through-holes are arranged in 7 columns and 7 rows (= 49 holes/device) in the center of the device, and are used there for selective wiring such as crossing of wires, interchange of electrodes, etc. On the outer periphery of the device, 7 through-hole interconnections are arranged on each side, i.e., there are 24 through-hole interconnections. These through-hole interconnections are used as electrodes for transmitting and receiving signals from the functional circuits placed above and below.

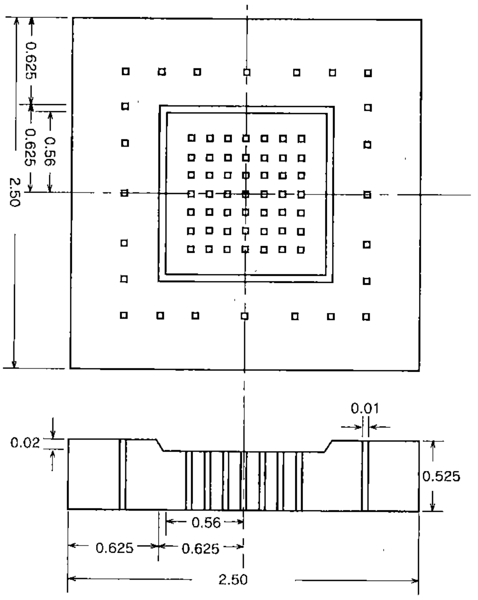


Fig. 16 Schematic representation of the through-hole interconnection chip (unit: mm)

The through-holes formed by the OEEM are as small as 10 μm square and large in aspect ratio, so conventional methods such as evaporation, sputtering, plating, CVD, etc., cannot be used to refill the through-holes with metal to form through-hole interconnections. Therefore, a new molten metal suction method of the open type was developed which refills the through-holes with metal by sucking molten metal in the air.

Figure 17 shows the cross section of the through-hole interconnection formed by refilling the through-hole with metal. The process of refilling the through-hole is described below. First, a diffusion layer for shielding was formed on the wall surface of the through-hole. For this, about 1.0 cm^3 of a liquid boron film [PBF: 3M-23 (B_2O_3 = 1.2wt%: viscosity = 23 cP)] was added dropwise to the wafer surface. The boron film was sucked into the through-hole in a vacuum of 7.0 x 10^{-2} Torr. Then, boron was diffused (1100 degrees C, O_2, 30 min) to obtain a diffusion layer depth of 2.5 μm and a surface dopant

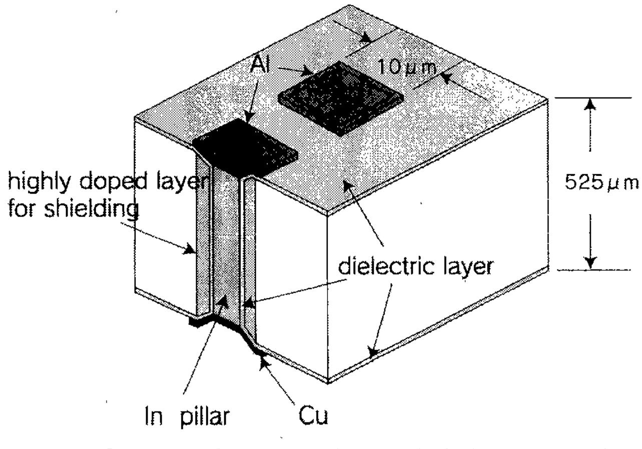
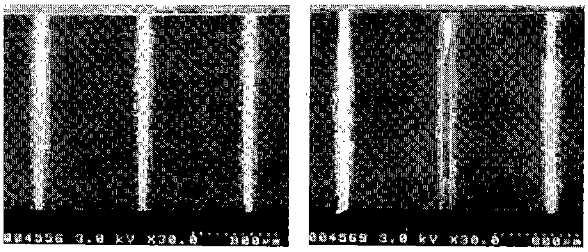


Fig. 17 Cross section of the through-hole interconnections



Good sample poor sample

Photo. 3 Cross section of the through-hole refilled with metal (In)

density of 1.0 x 10^{20} atoms/cm^3. The film thickness of SiO_2 grown on the wall surface of the through-hole was 500 nm, and a dielectric breakdown voltage over 300 V was secured. The criteria for selecting a metal with which to refill the through-hole are:

(1) Melting point below 400 degrees C for protection against degradation of the built-in function of the Si wafer

(2) Low vapor pressure at the melting point for suction by vacuum pump

(3) Low coefficient of cube expansion to prevent the sucked metal from forming voids due to shrinking with temperature drop or coming out of the through-hole

(4) Low resistivity of metal to decrease electric resistance

Based on these criteria, In, Hg, Pb, Sn and Zn were measured for viscosity, surface tension, etc., and investigated. As a result, indium was selected.

Photograph 3 shows the cross section of the through-hole refilled with metal by the open-type suction method. Figure 18 shows the surface profile of the metal sucked into the through-hole, measured using a laser type surface roughness tester. The measuring point is a diagonal of the In pillar top in Fig. 17. It seems that the large irregularities found in this figure were caused by the fact that the corners of the square-shaped hole were incompletely filled with metal, or part of the metal in the through-holes was pulled out when the excess molten metal remaining on the surface was removed with a squeegee.

In order to prevent the sucked metal from coming off due to subsequent heating or from forming voids and thereby to avoid possible variation in electric resistance, the V-pits on both surfaces of the device were sealed with a sputtered film of Cr (50 nm) and Cu (1,000 nm). The metal film on the bottom surface was used as an electrode for forming a solder bump by electroplating and was then patterned and left as the electrode.

By this open-type method, more than 90% of the through-holes with the aspect ratio of 52 or less could successfully be refilled with metal.

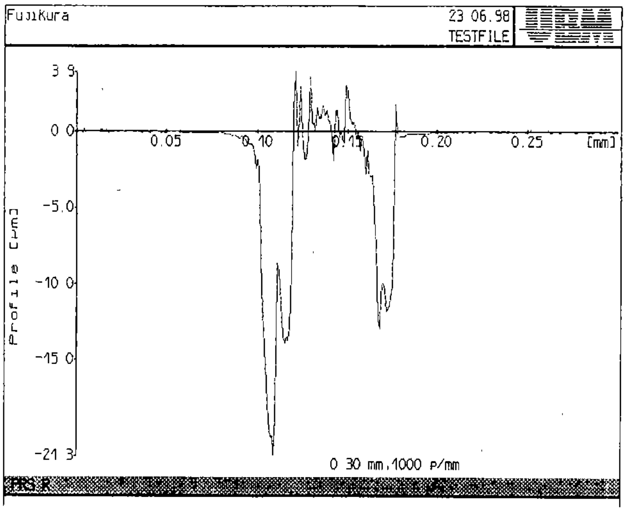


Fig. 18 The surface profile of the metal sucked into the through-hole

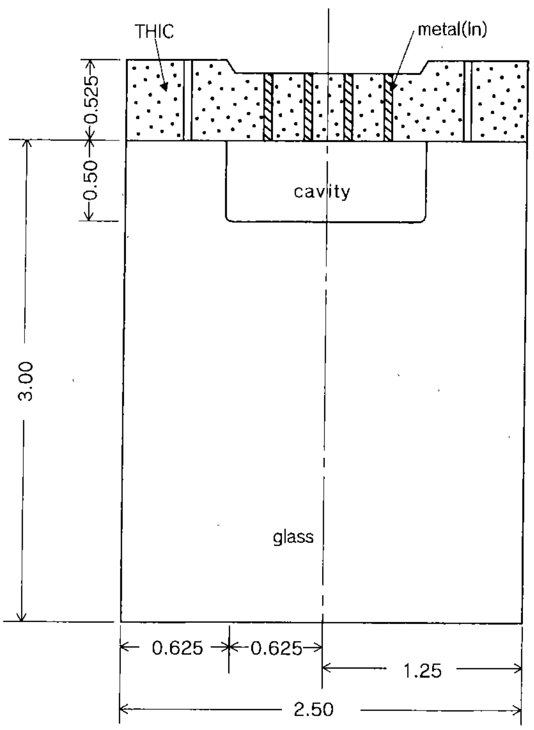
3-3. Evaluation of Through-hole Interconnections

Figure 16 shows the structure of the THIC device used in the evaluation of through-hole interconnections. An Al electrode was provided on the entire surface of the concavity (1 mm x 1 mm) in the center of the THIC device, and the capacitance between the Al electrode and Si wafer was measured at a frequency of 20 MHz. The measured value was 80 pF/hole. The dielectric breakdown voltage of the dielectric film placed on the wall surface of the through-hole was also measured on the specimen used for the capacitance measurement, and a value of over 300 V was obtained. The resistivity of the through-hole interconnections was measured with all the 16 interconnections of the THIC device connected in series, and a value lower than 100 mΩ/hole was obtained.

In order to check the gastightness of the through-hole interconnections, a 3.00 mm thick glass plate having a 0.78 mm^3 cavity was joined with the THIC device by anodic bonding as shown in Figure 19, and the Radiflo leak test [a micro-leak counting test by the irradiation of Kr-85 (a radioactive isotope of krypton)] was carried out. The result revealed that the through-hole interconnections are also excellent in gastightness, with no leakage exceeding the detection limit (1.0 x 10^{-10} Pa · m^3/sec).

4. Conclusion

Through-hole interconnections were fabricated by refilling the through-holes, formed by optical excitation electropolishing, with indium by the open-type molten metal suction method. The through-hole interconnections are high in density and aspect ratio and excellent in gastightness and, therefore, can be expected to find application in three-dimensional devices.



(unit: mm)

Fig. 19 Cross section of an inspection device to measure the air-tightness of the through-hole interconnections

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