KAWASAKI STEEL TECHNICAL REPORT
No.30 (August 1994)
Special Issue on LSI

Al/Al Direct-Contact Via Plug Formation Using Selective Al-CVD

Nobuyuki Takeyasu, Hiroshi Yamamoto, Tomohiro Ohta

Synopsis :
Direct-contact via plug of a submicron diameter with a novel via plug structure has been realized by selective aluminum chemical vapor deposition (Al-CVD). Lower and upper Al interconnects are directly connected with the plug of aluminum. Essential point of this technique is to carry out sequentially the following three processes without exposing wafers to the ambient: surface cleaning by reactive ion etching (RIE), plug formation by selective Al-CVD and sputter deposition of upper level Al film. The via structure has no heteromaterial interfaces across the current path. Electrical characteristics of the Al plug were evaluated and compared with those of the conventional W plug. The resistance of a via chain in 0.5-μm diameter was 0.24Ω/via, which was 1/3 that of the W-filled plug, and interface resistance was estimated to be extremely low. Electromigration (EM) tolerance of the new plug was better than that of the W plug. The direct-contact Al-CVD plug is, thus, very suitable for realizing high-performance LSI with lower process cost.

The body can be viewed from the next page.

Al/Al Direct-Contact Via Plug Formation Using Selective Al-CVD*



Nobuyuki Takeyasu
LSI Research Center, High-Technology Res. Labs.

Hiroshi Yamamoto
Dr. Eng., Staff Assistant Manager, Intellectual Property Dept.

Tomohiro Ohta
Dr. Sci., Senior Researcher, LSI Research Center, High-Technology Res. Labs.

Synopsis:

Direct-contact via plug of a submicron diameter with a novel via plug structure has been realized by selective aluminum chemical vapor deposition (Al-CVD). Lower and upper Al interconnects are directly connected with the plug of aluminum. Essential point of this technique is to carry out sequentially the following three processes without exposing wafers to the ambient: surface cleaning by reactive ion etching (RIE), plug formation by selective Al-CVD and sputter deposition of upper level Al film. The via structure has no heteromaterial interfaces across the current path. Electrical characteristics of the Al plug were evaluated and compared with those of the conventional W plug. The resistance of a via chain in 0.5-μm diameter was 0.25 Ω/via, which was 1/3 that of the W-filled plug, and interface resistance was estimated to be extremely low. Electromigration (EM) tolerance of the new plug was better than that of the W plug. The direct-contact Al-CVD plug is, thus, very suitable for realizing high-performance LSI with lower process cost.

1 Introduction

Recently, the device of very large-scale integrated circuits (VLSIs) has been scaled down, while operating speeds have increased. As the device is scaling down, the fabrication techniques for creating multilevel interconnects, planarizing interconnects and dielectric layers between the interconnects, and metallizing the interconnects become very important. Especially in metallization, an improved fabrication technique is required for the via plug connecting to both the lower and upper interconnects. In contrast to sputtering using a physical vapor deposition (PVD) method which can produce films with a smooth surface, the via filling technique using chemical vapor deposition (CVD) has been widely investigated, because its high step coverage makes it suitable for submicron via filling.

The blanket tungsten-CVD/etchback process is now widely used as a metallization technique in production lines. However, this process requires adhesion layer/nucleation layer deposition[1] and an etchback to remove W from areas except holes, which raises the process cost and involves more maintenance time for chamber cleaning to remove particles in order to maintain a product yield high. In addition, the W via structure has heteromaterial interfaces of Al-alloy/W and W/TiN/Ti/Al-alloy at the upper and lower sides of the W plug, requiring a TiN/Ti adhesion layer, as shown in **Fig. 1** (a). Such interfaces have the potential to cause a number of problems, e.g., high contact resistance,[2] degradation of electromigration (EM) by the inhibition of atomic migration,[3] and corrosion by local galvanic cells.[4] From these reasons, it is necessary to form the via structure without heteromaterial interfaces, as shown in Fig. 1 (b), at a lower cost. Aluminum-CVD

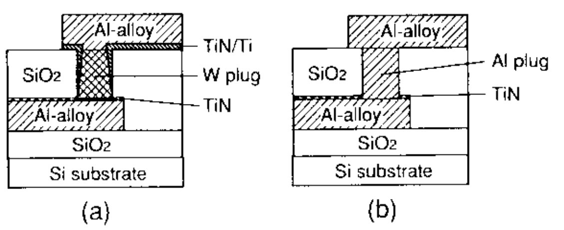

Fig. 1 Two different via structure; (a) conventional W plug, (b) the direct-contact Al plug proposed in this paper

* Originally published in *Kawasaki Steel Giho*, **26**(1994)2, 76–80

is a promising technique for satisfying these demands.

The metallization technique using Al-CVD has been investigated, using triisobutylaluminum (TIBA)[5-9] or dimethylaluminumhydride (DMAH)[10-14] as a source gas, and, recently, selective Al-CVD has been realized.[8-13] However, a via structure with CVD-Al plugs connected directly to the Al interconnect has not been reported. Because the native oxide on the Al surface prevents the growth of CVD-Al, one of the key issues for deposition of Al on Al is how to obtain a clean Al surface and to maintain it before Al-CVD. Thus, *in-situ* precleaning which can remove the native oxide is essential for depositing Al on Al. In the previous work on via filling using selective Al-CVD, it was only reported that selective Al-CVD with TIBA can be achieved on a Ti underlayer capped on the lower Al interconnects by the formation of an amorphous silicon mask layer and *in-situ* RF cleaning.[9] However, this process is considered complicated, and the via structure has heteromaterial interfaces.

This paper reports that an Al/Al direct-contact via structure can be formed by a simple process using *in-situ* reactive ion etching (RIE) precleaning and selective Al-CVD with DMAH in a high-vacuum cluster tool. In addition, the electrical characteristics of the new structure are compared with those of the conventional W via structure.

2 Experimental

In order to realize an Al/Al direct-contact via structure, it is necessary to prepare a clean Al surface, removing the native oxide just before CVD. **Figure 2** shows a high-vacuum cluster tool and the process steps used in this work to achieve Al-CVD on the cleaned Al surface. In this apparatus, the lower Al surface was cleaned by RIE precleaning, and the via hole was filled by selective Al-CVD, and the upper Al layer was then sputtered on it. These processes were performed continuously in the same vacuum with a base pressure of less than 1×10^{-7} Torr (1.33×10^{-7} hPa). First, RIE was performed using BCl_3 and Ar as process gases at a pressure of 0.05–0.15 Torr (0.0665–0.1995 hPa), and the substrate was placed on a carbon suscepter heated with a resistance heater in a cold-wall CVD reactor. DMAH as a metalorganic precursor was evaporated at room temperature and was supplied to the reactor with carrier H_2 gas, 500 sccm (0.844 $Pa \cdot m^3/s$), at a deposition temperature of 210–260°C, and total pressure of 2.0 Torr. Next, an upper Al layer (0.5 μm) was formed by sputtering and patterned to examine the characteristics of the Al plug. The substrates were prepared by etching a 1 μm-thick PECVD SiO_2 film and 0.05–0.1 μm-thick TiN antireflection layer on the lower Al alloy interconnect by conventional RIE to make via holes 0.3–0.8 μm in diameter.

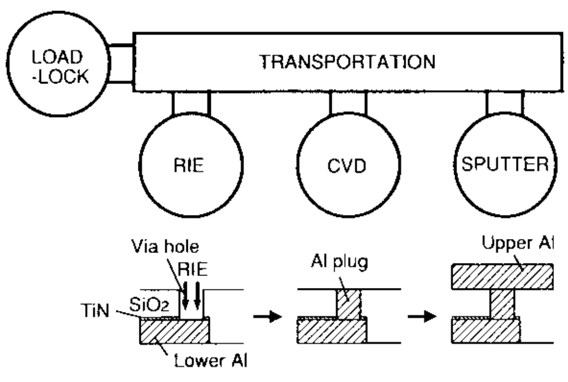

Fig. 2 Schematic diagram of the cluster tool used in this study, and the process steps to fabricate direct-contact via plug

The selective deposition and via filling of Al were observed by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Electrical characterization, via resistance and interface resistance, and electromigration (EM) tests were carried out after the formation of the upper Al interconnect and annealing at 400°C for 60 min. Samples with conventional W plugs were also made for comparison.

3 Results and Discussion

3.1 Plug Formation

In order to investigate the effect of RIE precleaning on Al-CVD applied to an Al substrate, blanket Al-CVD was performed on a sputtered Al film under the CVD conditions (CVD temperature, 260°C and total pressure, 2.0 Torr). Al was not deposited on thermal silicon oxide, but rather was deposited on Si. As shown in **Photo 1**, a continuous Al-CVD film could not be deposited without the precleaning step, while a smooth continuous film was deposited following *in-situ* RIE precleaning. This result suggests that the oxidized layer on the sputtered Al film, which was formed during air exposure, suppresses the deposition of the CVD-Al film under these CVD conditions but is successfully removed by the RIE precleaning.

After *in-situ* RIE precleaning, Al-CVD was performed on the substrate with via holes at 210°C. **Photo 2** shows cross-sectional SEM micrographs of Al plugs in 0.6 μm via holes at three different deposition times. It was found that the Al grew only from the bottom Al surface in the via holes, and the Al plugs were formed selectively on the Al surface. Selectivity was maintained even after the point in time when the holes were overfilled (15 min). On the other hand, it was found that only slight deposition occurred in the via holes from the bottom Al surface, and deposition occurred preferentially

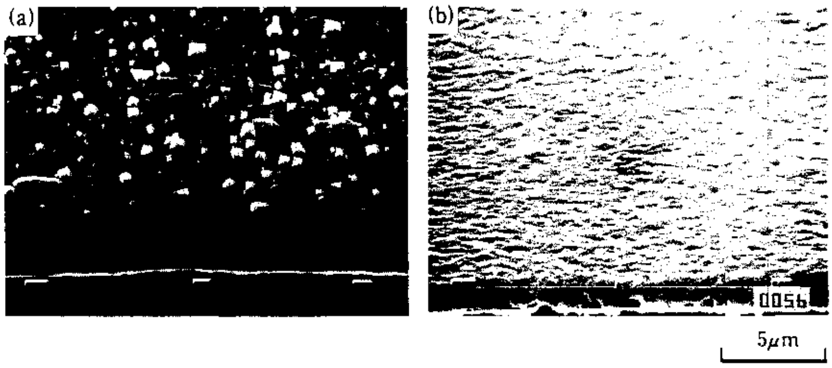

Photo 1 SEM micrographs showing blanket Al-CVD on the Al film substrates; (a) without and (b) with *in-situ* RIE precleaning

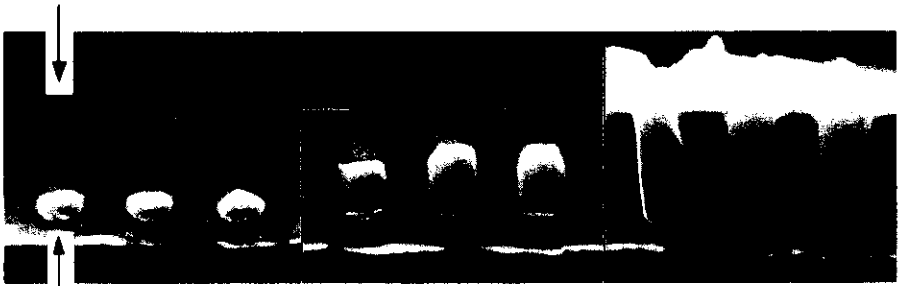

Photo 2 Cross-sectional SEM micrographs of the Al plugs in 0.6 μm via holes at 3 different deposition times

on the SiO_2 film after excessive exposure to the CVD ambient without the RIE precleaning. These results demonstrated that the *in-situ* RIE precleaning is essential to realize selective Al deposition in the via hole.

The direct-contact Al plugs formed in 0.45 μm via holes using *in-situ* RIE precleaning and selective Al-CVD are shown in **Photo 3**. The deposition time was 5 min. It was found that the deposition rate can be increased while maintaining superior selectivity if the deposition conditions are optimized based on an understanding of the characteristics of Al-CVD.[15] Smaller via holes with a diameter of 0.3 μm can also be filled with Al plugs by selective Al-CVD. Unlike the results of deposition with TIBA as a source gas,[16] the deposition rate was found to be independent of via size in the range of 0.3–0.8 μm in diameter. This characteristic is advantageous in the application of the Al-CVD plug to actual LSIs with various via hole sizes.

The cross-sectional TEM observation, as shown in **Photo 4**, indicated that the via holes are fully filled with

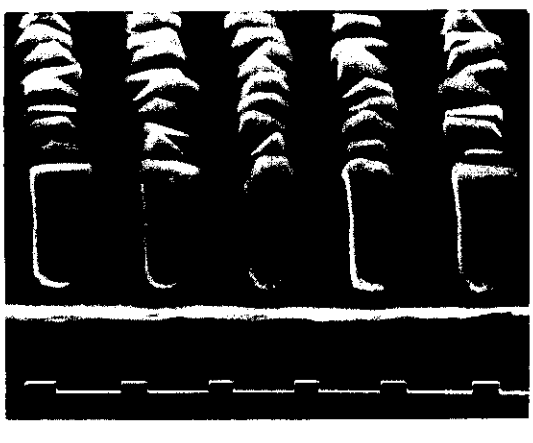

Photo 3 SEM photograph of the CVD-Al plugs formed in 0.45 μm via holes on 5 min deposition

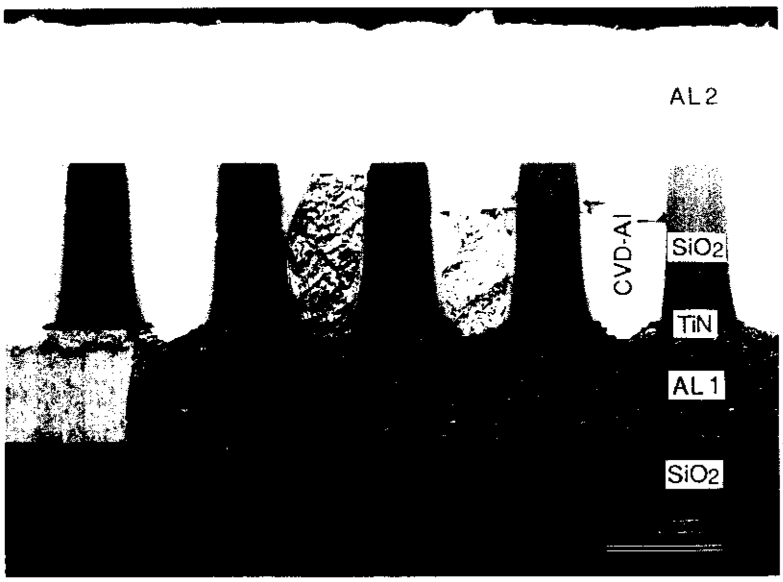

Photo 4 Cross-sectional TEM photograph of the direct-contact via structure fabricated in this study

Al plugs having no voids and that the plugs contact both the lower and upper interconnects without any intermediate layers.

3.2 Electrical Characterization

Figure 3 shows via chain resistance as a function of via hole size for the Al/Al direct-contact via structure fabricated in this work and a conventional W via structure, as shown in Fig. 1 (a). The resistance with the former was lower than that with the latter, and the difference became larger as the via hole size decreased. The 0.5 μm via chain resistance of the new structure was 0.25 Ω/via, which was about 1/3 that of the W via structure. The via resistance of the new structure was also measured by the Kelvin method. The 0.5 μm Kelvin resistance was about 0.2 Ω and was about 1/2 that (about 0.4 Ω) of the Al plug with heteromaterial interfaces of Al/Ti/Al.[8] It is considered that the via resistance of the Al/Al direct-contact via structure was extremely low, partly because the plug material was Al, which has low resistivity, but mainly because this structure had no heteromaterial interfaces.

The measured via resistance R_c consists of the upper and lower line resistances, R_u and R_l, the plug resistance R_p, and the interface resistance R_i, as shown in **Fig. 4**. We calculated R_u, R_l and R_p using the values of 3 and 10 μΩ·cm as Al and W resistivities, respectively. The interface resistance was estimated using Eq. (1).

$$R_i = R_c - (R_u + R_l + R_p) \quad \cdots\cdots (1)$$

The estimated interface resistances for the direct-contact Al plug and the W plug were compared as a function of reciprocal via hole area, d^{-2}, as shown in **Fig. 5**.

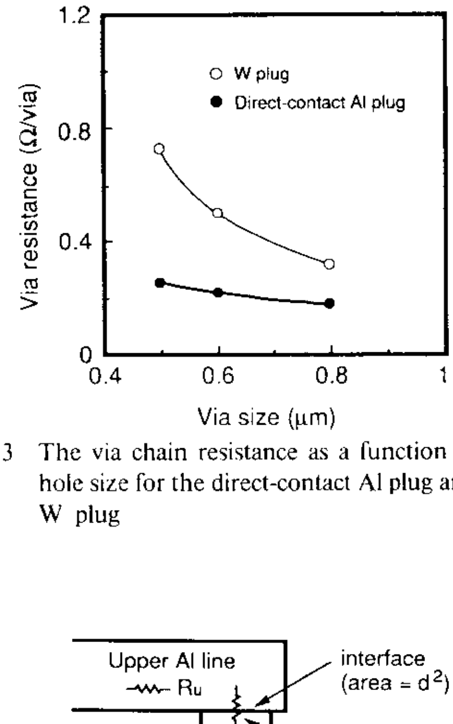

Fig. 3 The via chain resistance as a function of via hole size for the direct-contact Al plug and the W plug

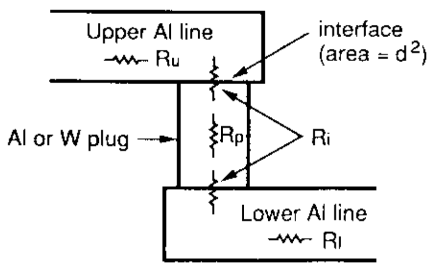

Fig. 4 The cross section of a via structure (The via resistance consists of the upper and lower line resistances, the plug resistance and the interface resistance.)

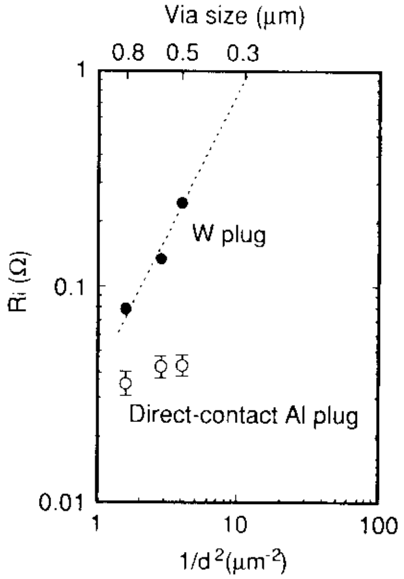

Fig. 5 Calculated interface resistance as a function of the reciprocal of via hole area, d^{-2}, for the direct-contact and W plugs

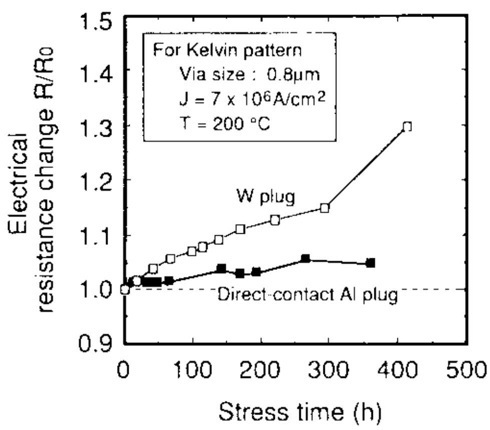

Fig. 6 The resistance increase of the direct-contact Al plug and the conventional W plug under the conditions of 200°C and 7×10^6 A/cm^2 stress

Error bars in this figure represent the 10% error in the evaluation of R_u, R_l, and R_p. This figure shows that the interface resistance of the W plug increases rapidly with decreasing via size. On the other hand, the interface resistance of the direct-contact Al plug is about 0.04 Ω and is considered to be extremely low.

Electromigration tolerance was evaluated using an unpassivated 0.8 μm Kelvin pattern. **Figure 6** shows the electrical resistance change during an EM test conducted at an ambient temperature of 200°C and a stress current density of 7×10^6 A/cm^2. The resistance change of the direct-contact Al plug was smaller than that of the W plug. This result suggests that the EM tolerance of the direct-contact Al plug is superior to that of the W plug. It is considered that this higher reliability of the Al plug was achieved because there were no hetero-material interfaces. In addition, perfect filling without voids, shown by the TEM photograph, is considered to be a reason for this higher reliability. Furthermore, the characteristics may be improved by applying AlCu alloy CVD.[17)]

4 Conclusions

An Al/Al direct-contact via structure by a simple process has been developed by carrying out *in-situ* RIE precleaning and selective Al-CVD sequentially under a high vacuum. The *in-situ* RIE precleaning was found to be essential to realize selective Al deposition in the via hole. The new structure had lower via resistance and interface resistance, and superior EM tolerance to that of a W plug, presumably because it had no heteromaterial interfaces. In the future, direct-contact Al-CVD plugs are expected to be applied in place of W-CVD plugs to realize high-performance LSIs and low-cost processes.

References

1) M. Iwasaki, H. Itoh, T. Katayama, K. Tsukamoto, and Y. Akasaka: "Blanket CVD-W Formed by SiH_4 Reduction of WF_6 on TiN for Planar Interconnection," Ext. Abstr. of the 21st Int. Conf. Solid State Devices and Materials, The Japan Society of Applied Physics, Tokyo (Japan), August (1989), 41
2) S. R. Wilson, J. L. Freeman, and C. J. Tracy: "A High Performance Four Metal Layer Interconnect System for BIPOLAR and BIC-MOS Circuits," Proc. 7th Int. IEEE VMIC, IEEE Electron Devices Society, Santa Clara (USA), June (1990), 42
3) J. J. Estabil, H. S. Rathore, and E. N. Levine: "Electromigration Improvements with Titanium Underlay and Overlay in Al (Cu) Metallurgy," Proc. 8th Int. IEEE VMIC, IEEE Electron Devices Society, Santa Clara (USA), June (1991), 242
4) A. J. Griffin, Jr., S. E. Hernandez, F. R. Brotzen, J. D. Lawrence, J. W. McPherson, and C. F. Dunn: "Corrosion Behavior of Thin-film Metallizations on CVD W and Sputtered W-Ti Barrier Layers," Proc. 31st IRPS, IEEE Electron Devices Society, Atlanta (USA), March (1993), 327
5) M. J. Cooke, R. A. Heinecke, R. C. Stem, and J. W. C. Maes: *Solid State Technol.*, **25**(1982), 62
6) R. A. Levy, M. L. Green, and P. K. Gallagher: *J. Electrochem. Soc.*, **131**(1984), 2175
7) A. Sekiguchi, T. Kobayashi, N. Hosokawa, and T. Asamaki: *Jpn. J. Appl. Phys.*, **27**(1988), L1775
8) T. Amazawa and Y. Arita: "A 0.25 μm Via Plug Process Using Selective CVD Aluminum for Multilevel Interconnection," Ext. Abstr. Int. Electron Device Meet., IEEE Electron Devices Society, Washington, D.C. (USA), Dec.

(1991), 265
9) T. Amazawa and H. Nakamura: "Selective Chemical Vapor Deposition of Aluminum", Ext. Abstr. of the 18th Int. Conf. Solid State Devices and Materials, The Japan Society of Applied Physics, Tokyo (Japan), August (1986), 755
10) T. Shinzawa, K. Sugai, S. Kishida, and H. Okabayashi: "Selective Al CVD Using Dimethyl Aluminum Hydride," Workshop on Tungsten and Other Advanced Metals for VLSI/ULSI Applications V, Mater. Res. Soc., San Mateo (USA), September (1990), 377
11) K. Tsubouchi, K. Masu, N. Shigeeda, T. Matano, Y. Hiura, and N. Mikoshiba: *Appl. Phys. Lett.*, **57**(1990), 1221
12) H. Kawamoto, H. Sakaue, S. Takehiro, and Y. Horiike: *Jpn. J. Appl. Phys.*, **29**(1990), 2657
13) K. Tani, T. Yamaji, and S. Nishikawa: *Jpn. J. Appl. Phys.*, **31**(1992), 4407
14) K. Sugai, T. Shinzawa, S. Kishida, H. Okabayashi, Y. Murao, T. Kobayashi, N. Hosokawa, T. Yako, H. Kadokura, M. Isemura, and K. Kamio: "Sub-half Micron Aluminum Metallization Technology Using a Combination of CVD and Sputtering," Proc. 10th Int. IEEE VMIC, IEEE Electron Devices Society, Santa Clara (USA), June (1993), 463
15) H. Yamamoto, E. Kondoh, N. Takeyasu, Y. Kawano, T. Katagiri and T. Ohta: "Realization of Direct-contact Via Plug by Use of Selective Al-CVD," Proc. 44th Symp. on Semiconductors and Integrated Circuits Technology, Electrochemical Society of Japan, Electronic Materials Committee, Tokyo (Japan), June (1993), 79 [in Japanese]
16) T. Amazawa and Y. Arita: "Fine Via-Hole Filling by Selective Aluminum Deposition," Ext. Abstr. 50th Autumn Meet. Japan Society of Applied Physics and Related Societies, The Japan Society of Applied Physics, Tokyo (Japan), September (1989), 29p-D-3
17) T. Katagiri, E. Kondoh, N. Takeyasu, T. Nakano, H. Yamamoto, and T. Ohta: *Jpn. J. Appl. Phys.*, **32**(1993), L132