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Mass Transport Mechanism of Molten Metal in Excimer Laser Induced Plug Formation for Submicron Interconnection

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A mass transport mechanism of metal molten by an excimer laser irradiation for submicron via hole filling has been cleared up. In this via filling, a thin metal cap which is patterned to be covering enough the entire via hole is used, followed by melting with a XeCl excimer laser irradiation. The molten metal cap is drawn to the via during the mass transport procedure, resulting in formation of the metal plug. In this paper we propose the mechanism that is based on the surface tension forces created by the three-dimensional geometry of the molten metal film. A knowledge of mechanism is needed in order to produce easily and stably a metal plug to achieve submicron interconnection.

1. Introduction

A promising laser planarization technique was demonstrated for submicron interconnection [1]. In the present technique, sputter-deposited metal films are melted by pulsing from an excimer laser, resulting in realization of the planarization and via hole filling. The presence of undesired voids in via holes of aspect ratio greater than 1 can be observed. Such voids have been eliminated by heating substrate [2]. In the present case, the substrate was kept at 300 ℃ during the laser irradiation. However, the mechanism to fully fill submicron via hole was not identified in this report. The mechanism responsible for this void formation was discussed in the previous reports [3,4].

In this paper we discuss minutely the mechanism for undesirable void formation, and propose a mass transport mechanism of laser-melted metal for submicron via hole filling.

2. Laser Plug Formation Technique

In Fig.1 we show the explanation of laser-plug-formation technique. In this work, the metal films are patterned to be a square shape. The square shape is arranged to be covering enough the entire via hole. The patterning controlles the total amount of metal which is filled in the via hole. A metal cap is fabricated by this patterning, followed by melting with a XeCl excimer laser (wavelength: 308 nm) irradiation. During the laser irradiation, a sample was kept at room temperature. The molten metal cap is drawn to the via during the desired mass transport procedure, resulting in formation of metal plug.

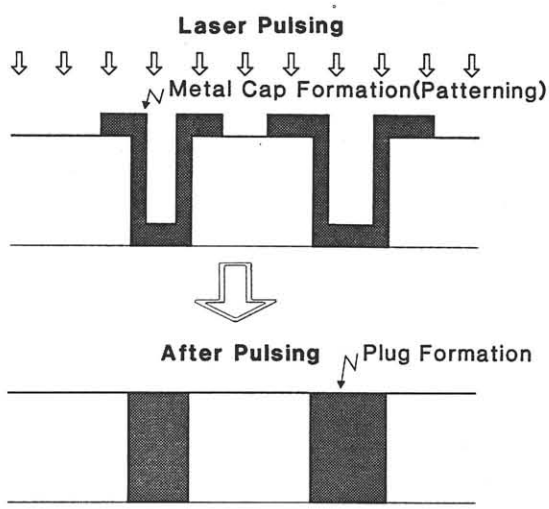


Fig.1. Explanation of the excimer-laser-plug-formation technique.

The cap was composed of a 200nm-thick thin metal (Ti or Al) film which was patterned to be the square. The thin metal films were deposited by a conventional sputtering. The patterning was achieved by a conventional electron beam (EB) lithography and reactive ion etching (RIE). The thin metal films (<500 nm) are needed especially if the laser melting is achieved by the pulsing at a low fluence (<0.75 J/cm^2). The beam size of pulsing should agree with a VLSI chip area (~2X2 cm) in order to melt easily and stably the metal film. For keeping the beam size, the pulsing at the low fluence is needed because the pulse energy up to ~4J/Pulse is limited on a usual excimer-laser-irradiation system (optical transmission: ~75%).

The via holes were opened in an insulator selectively by EB lithography and RIE for

connecting to the underlying Al line on a 1 μm-thick SiO_2 over a Si substrate. The insulator consisted of a phosphosilicate glass (PSG).

Figure 2 shows a schematic of laser irradiation system. The optical pulses have been focused with the optical system for increasing its optical fluence. The system redefined and homogenized the laser beam, and was mounted on an X-Y stage which tracked the beam across the sample.

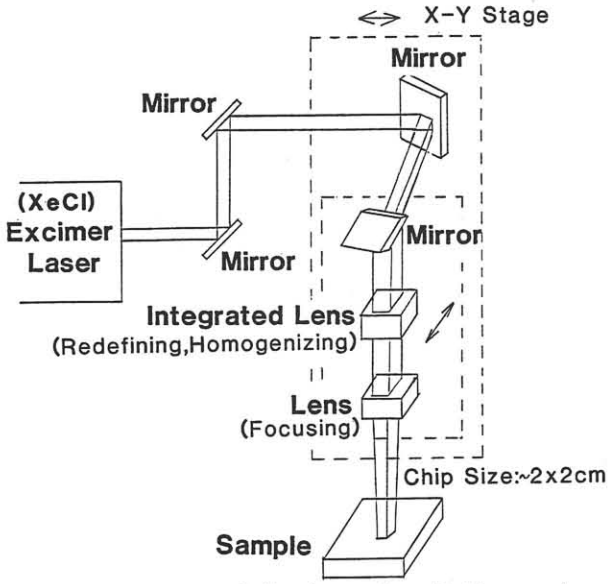


Fig.2. Schematic of the laser irradiation system.

3. Mass Transport Mechanism of Molten Metal

A temperature distribution with time in the metal cap heated by the laser irradiation is calculated by two-dimensional conduction equation of heat. The mechanism to fully fill submicron via hole may be obtained through a study that is based on the experimental examination and the calculation.

Figure 3 shows a schematic illustration of the mass transport mechanism for plug formation.

In the 1st step, the thin metal cap is melted by the laser irradiation. The sidewall metal must be melted fully at this step. In the 2nd step, the mass transport of molten metal occurs. The molten metal rings itself round the via and then closes off the top of via. The surface tension forces responsible for the closing are created by the formation of ring. The calculated pressure is about 1.0×10^8 dyn/cm^2 in the case of 0.7 μm via. The thin metal films are usually balled up due to an undesirable mass transport of metal during the laser melting procedure. The ballup problem can be solved by this formation of ring. The top of via is closed off in the 3rd step, resulting in formation of the void. In this condition, the base of molten metal makes a concave shape. The surface tension forces generated by the concave shape act in order to eliminate the void. The calculated pressure is about 0.9×10^8 dyn/cm^2 in this case. In the final step, the via is filled fully by this elimination of void.

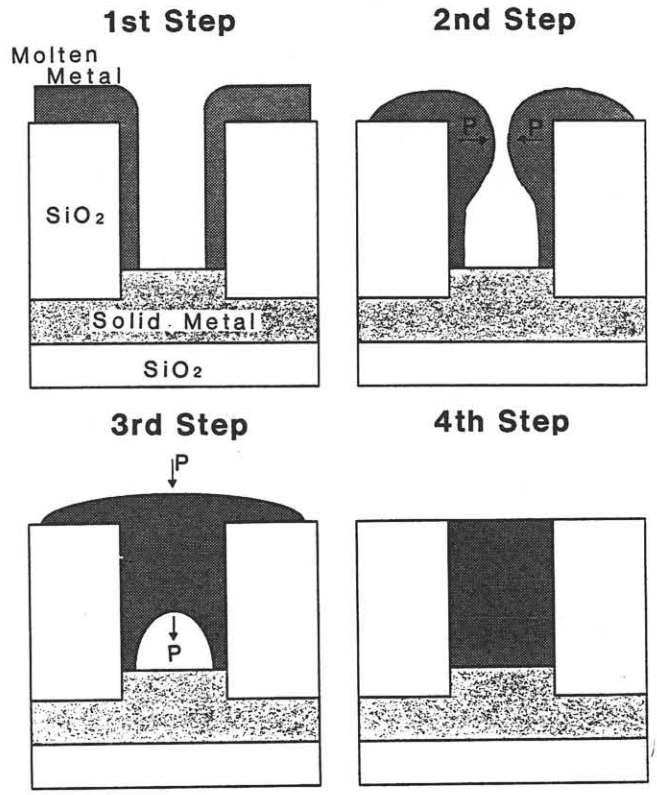


Fig.3. Schematic illustration of the mass transport mechanism that is based on the surface tension forces created by three-dimensional geometry of the molten metal cap. In the figure, a local pressure discontinuity at any surface element is marked with $\triangle P$.

4. Characterization of The Mass Transport

A formation of metal plug is realized by a mass transport of laser melted metal. In this paragraph we indicate the characterization of mass transport for elucidation of the mechanism.

We observed the via hole in samples before and after the laser melting. The Al cap was not fully deposited on the sidewall of vias whereby the metal melted by laser irradiation was pinned at the top of via. The resulting condition included an undesired void in via hole. In the Ti cap, the pinning problem was solved because the metal was fully deposited on the sidewall of vias. This result suggests that the sidewall metal must be deposited in order to fully fill submicron via hole.

An insufficient melting of metal cap also brings the pinning problem.

We investigated the effect of increasing optical fluence on the mass transport of molten Ti cap. A location of interface between molten metal and solid metal on the sidewall was changed by the variety of different optical fluences. The molten metal was pinned at the location of the interface. These resulting condition suggest that the sidewall metal must be melted fully at the laser melting procedure.

The present of voids can not be avoided by the mere elimination of pinning problem.

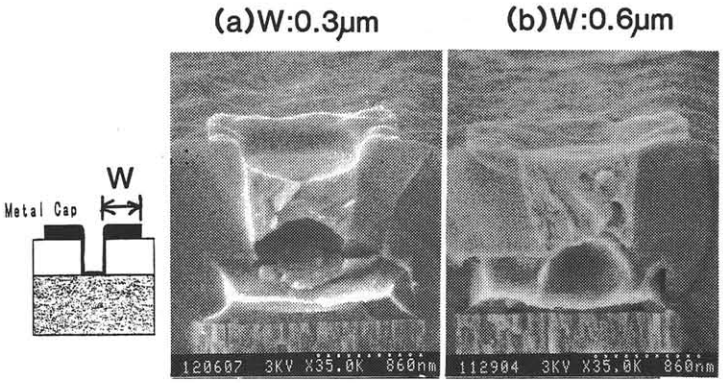


Fig.4. SEM micrographs showing the via hole which is filled with a variety of different total amount of metal to be melted. The via size is 0.7 μm with 1.0 μm depth. The all laser melting is achieved by the pulsing the low fluence (0.58 J/cm^2).

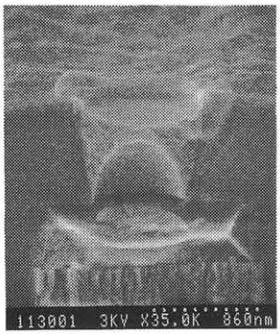


Fig.5. A SEM micrograph showing the via hole which is filled with the short melt time. The via size is 0.7 μm with 1.0 μm depth.

Figure 4 is SEM micrographs showing the via hole which is filled with a variety of different total amount of metal to be melted. The total amount of metal is controlled by the patterning to produce metal cap. In this case, the sidewall metal is melted fully at the laser melting procedure. However, the presence of undesired void is observed in the filling at a little total amount of metal, as shown in Fig.4(a). In this condition, the top and bottom of molten metal which are drawn to the via makes a same concave shape. The surface tension forces for moving the molten are generated equally by these concave shape. However, these forces act to the opposite direction each other whereby the mass transport is stopped. This result suggests that the mass transport of molten metal in via is stopped by a surface tension force generated by the concave shape which is made in the top. The enough total amount of metal is also needed due to the prevention of void formation, as shown in Fig.4(b).

However, the enough melt time of metal is needed, too. In the short melt time, the undesired void is produced because the mass transport acted by the surface tension forces is interrupted by the solidification of molten metal, as shown in Fig.5.

In Fig.6 we indicate the summary of undesirable void formation.

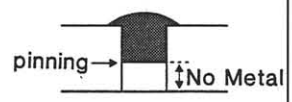
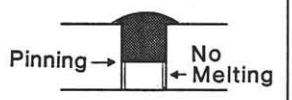
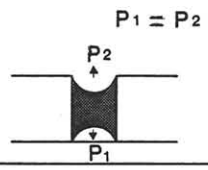
Parameter	Result
Nonuniform Metal Deposition on Sidewall	
Fluence Shortage	 (Short Melt Time) 
Less Volume of Metal	

Fig.6. The summary of undesirable void formation.

Table 1. Requirement for Laser Plug Formation.

Parameter	Requirement
Deposited Metal Condition	Deposition on Via Sidewall
Optical Fluence	Full Melt of Metal Cap Enough Melt Time
Total Amount of Metal	$\geq$ Volume of Via Hole

Therefore, the requirements for laser plug formation are summarized by four subjects, as shown in Table 1.

5. Conclusion

We have proposed the plug formation mechanism that is attributed to the surface tension forces created by the three-dimensional geometry of the laser-melted metal.

References

[1] R.Mukai, N.Sasaki and M.Nakano; IEEE Electron Device Lett.,8(1987) p.76.
[2] R.Mukai, N.Sasaki and M.Nakano; in Proc. Matl. Res. Soc. Symp.,74(1987) p.229.
[3] P.F.Marella, D.B.Tuckerman and R.F.Pease; Appl. Phys. Lett.,56(1990) p.2625.
[4] A.F.Bernhardt, R.J.Contolini, D.B.Tuckerman and A.H.Weisberg; in Proc. Matl. Res. Soc. Symp.,129(1989) p.559.