Extended Abstracts of the 1996 International Conference on Solid State Devices and Materials, Yokohama, 1996, pp. 115-117 

# Gap-Filling of Cu Employing Self-Sustained Sputtering with ICP Ionization

Takanori ICHIKI, Toshiaki KIKUCHI, Atsushi SANO*, Shoso SHINGUBARA* and Yasuhiro HORIIKE

*Department of Electrical & Electronics Engineering, Toyo University, 2100 Kujirai, 350, Kawagoe.*
**Department of Electrical Engineering, Hiroshima University, 1-4-1, Kagamiyama, 724, Higashi-Hiroshima.*

Copper filling of high aspect-ratio gaps has been investigated systematically using self-sustained sputtering with ICP ionization. In order to understand gap-filling characteristics, deposition and/or resputtering rates have been mainly measured as a function of the substrate bias, ICP power, and the incident angle of ions to the substrate. Since Ar ions are excluded from the plasma, considerable improvement of the bottom coverage has been achieved with proper substrate biasing. The present paper also shows both the limiting problems and the possibility of the high aspect-ratio hole filling by this method.

## 1. INTRODUCTION

With scaling down of VLSI's to the sub-half micron regime, reliability problems due to electromigration and RC delay time have become more critical issues in multi level interconnections. Cu is a promising candidate for the future interconnection material to replace Al alloys since it shows low resistivity and long electromigration lifetime. In order to realize Cu interconnect, Cu CVD has been intensively investigated so far. However, its use in industrial IC manufacture might be limited due to the expensive liquid sources. On the other hand, sputter deposition has advantages of low cost and also simpler process steps, while conventional sputter deposition is not suitable for filling of high aspect-ratio gaps. Consequently, several types of improved sputter deposition has been reported such as collimated sputtering, ionized magnetron sputtering, self-sustained sputtering and so on[1-3]. Among them, bias sputtering is expected to be an effective method with the advantage of the higher resputtering rate on the top surface than that inside a narrow trench. However, our recent study of bias sputter filling of Cu using magnetron sputter source with ICP ionization has revealed an unexpected problem that excess resputtering of Cu film, probably by Ar ions reflected from the sidewall, was observed especially at the bottom of the trench as shown in Fig. 1.

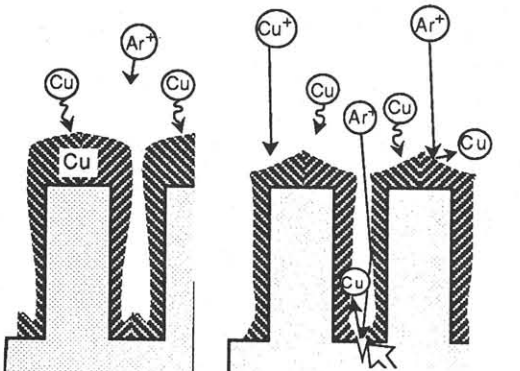


Fig. 1. Schematics of the trenches filled by magnetron sputtering with no substrate bias (a) and with substrate bias of a few hundred V.

In the present paper, bias sputter filling of Cu using a self-sustained sputter source and an auxiliary ICP ionization antenna is reported. The self-sustained sputter source[4] does not use inert gas, e.g. Ar, in contrast to conventional magnetron sputter source and hence enables to solve the problem of excess resputtering at the bottom.

## 2. EXPERIMENT

Figure 2 shows the apparatus employed in this study. The base pressure of the apparatus evacuated with cryopump was $2 \times 10^{-7}$ Torr. With supplying Ar into the chamber, at first discharge was initiated at 3 mTorr. Then Ar was stopped and immediately evacuated to shift to the self-sustained sputtering. Target power was $600 \times 9.7$ VA. A large portion of Cu atoms sputtered from the target were ionized by 13.56 MHz single-turn inductive coupling antenna, which was located at the middle of the target and the substrate, and then accelerated to the DC biased substrate. Depositions were typically carried out in the ICP power range from 0 to 600 W and the substrate bias range from 0 to -150 V at the target-substrate distance of 150 mm.

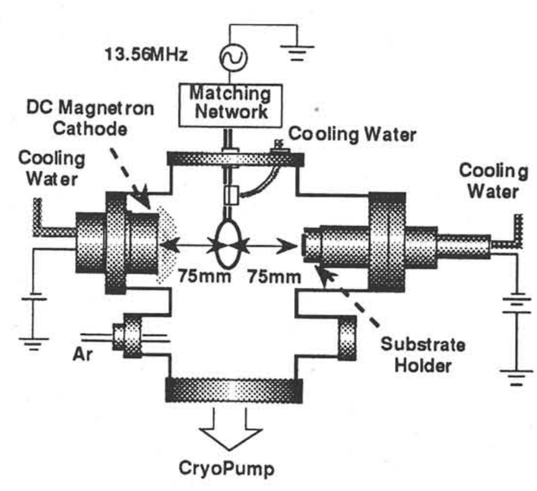


Fig. 2. Schematic diagram of the sputtering apparatus employed in this study.

## 3. RESULTS AND DISCUSSION

### 3.1. ICP ionization

Generation of pure Cu ICP was confirmed by measuring saturation ion current density with increasing an RF power supplied to the antenna. As shown in Fig. 3, at the ICP power of 600 W the Cu ion flux in the vicinity of the substrate was 3 to 4 times higher than that in the case without ICP. In addition, plasma potential variation from 3 V to 23 V was observed when an RF power was increased from 0 W to 600 W.

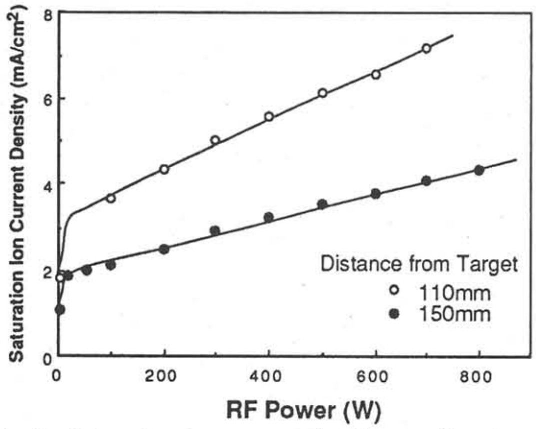


Fig. 3. Saturation ion current density as a function of the RF power coupled to the antenna.

### 3.2. Resputtering rate

In Fig. 4 the deposition rate on the planar substrate is plotted against the substrate bias. The larger slope of the line in the case with ICP ionization than that in the case without ICP is explained by the higher resputtering rate due to the higher ion flux to the substrate. Thus ICP ionization surely enabled the wide range control of the resputtering rate, which is one of the most important parameter to determine whether a high aspect-ratio gap can be filled or not.

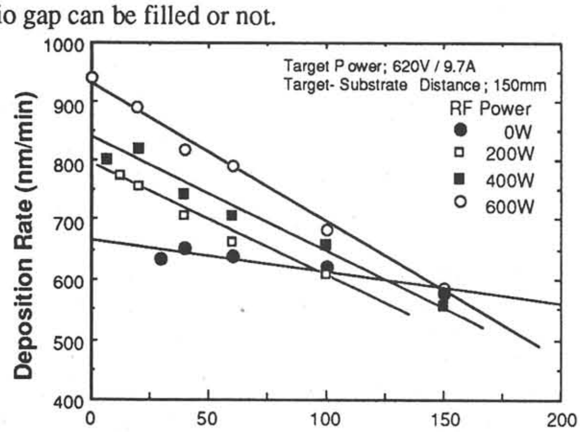


Fig. 4. Substrate bias dependence of the deposition rate of Cu on the planar substrate.

Subsequently angular dependence of the resputtering rate was investigated by using the experimental configuration as shown in Fig. 5. Apparent resputtering rates plotted in Fig. 6 were estimated from differences in deposition rates with and without the substrate bias. These curves are explained by the angular dependence of two factors: the sputtering yield and the cosine dependent ion flux. According to the linear cascade theory, the sputtering yield rises in proportion to $\cos^{-n}\theta$, and rapidly decreases at higher incident angles due to the reflection of ions from the surface. A maximum of the resputtering rate was observed at around 30-50 deg.

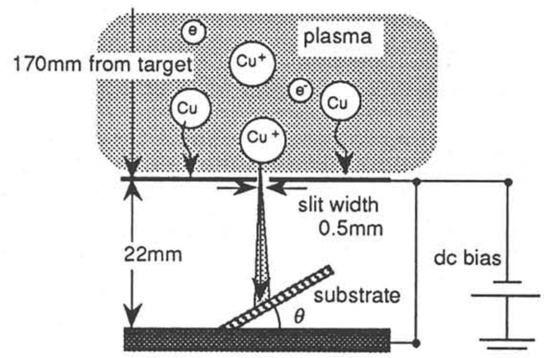


Fig. 5. Experimental configuration employed to investigate angular depencence of resputtering rate.

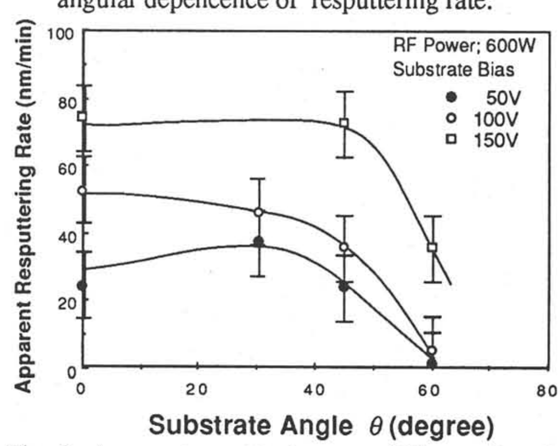


Fig. 6. Apparent resputtering rate of Cu as a function of the substrate angle $\theta$.

### 3.3. Gap filling

A series of depositions were carried out on substrates with etched trenches of depth 2.7 μm and various widths from 0.5 μm to 2 μm. Even at low RF power and low bias voltage relatively wide trenches of 1 μm were fully filled up, while narrower trenches were enclosed to form internal voids before filled up due to the great accumulation of Cu on the top surface. Figure 7 shows the substrate bias dependence of $T_b/T_t$ ratio for the samples deposited at the high ICP power of 600 W for 2 min, where $T_b$ and $T_t$ are the film thickness deposited on the bottom of the trench and that on the top surface, respectively. In the case of conventional sputtering $T_b/T_t$ ratio is always less than unity, and $T_b/T_t > 1$ means the effective bias sputter filling is achieved. Indeed, at the low bias voltage less than 100 V $T_b/T_t$ was less than unity, while at -150 V it increased to around 2 because of the sufficient resputtering on the top surface and the increased deposition rate on the bottom surface. Further more, $T_b/T_t > 1$ was achieved only under high ICP power condition of 600 W. Figure 8 shows the cross-sectional SEM of the trenches filled at 600 W and -150 V for 2 min.

Figure 9 shows the facet angle of Cu deposited on trench

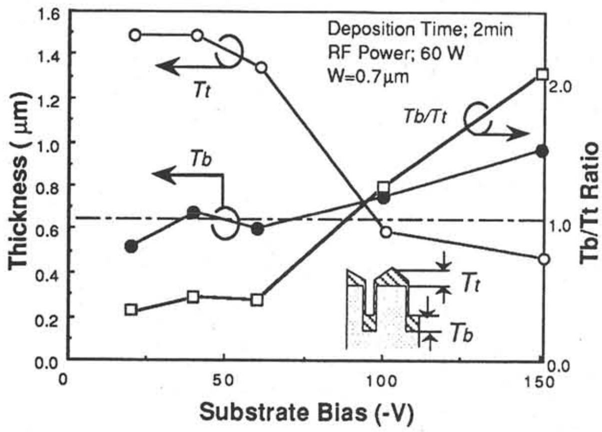


Fig. 7. Effects of the substrate bias on $T_b$, $T_t$ and the $T_b/T_t$ ratio.

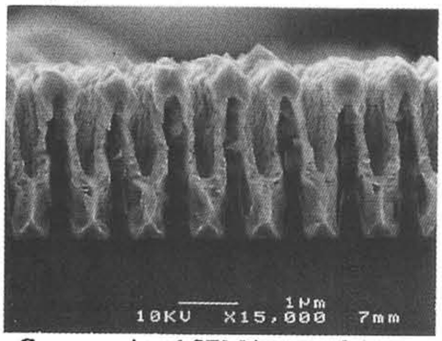


Fig. 8. Cross-sectional SEM image of the trenches of 0.7 μm width filled at 600 W and -150 V.

patterns with various widths as a function of the substrate bias. With the increase of the substrate bias, the angles from horizontal surfaces gradually decrease to the certain values. Such angle dependence is considered to reflect the resputtering characteristics as revealed in Fig. 6. Moreover, it is also noted that the facet angles tend to be smaller for narrower trench widths. This is probably resulted from the unnegligible deposition of Cu atoms resputtered or reflected from neighbors. In fact, substrate biasing could hardly suppress the sidewall deposition and rather seemed to enhance the deposition near the opening of the trenches. Therefore bias voltage should be selected properly so as to balance two competitive effects: (1) resputtering on the top surface and (2) redeposition on the sidewall. Overhanging sidewall growth makes it very difficult to fill up narrow gaps.

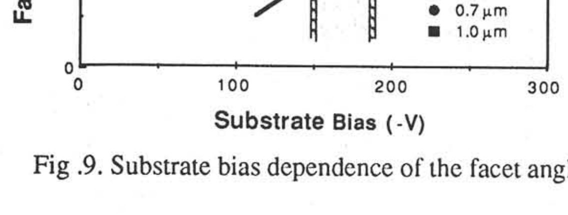


Fig .9. Substrate bias dependence of the facet angle.

Since increasing substrate temperatures can be expected to improve the structure of sidewall depositions, preliminary experiments of contact hole filling have been carried out on substrates without water cooling at the shorter target-substrate distance of 110 mm, where the ion current is about 1.7 times larger than that at 150 mm as shown in Fig. 3. As shown in Fig. 10, excellent solid filling of contact holes with an underlayer of 50 nm TiN was achieved with the following substrate biasing. At first, a rather high bias voltage of -300 V was applied for 1 min, and then followed by -150 V for 2 min. In this experiment, the temperature rise due to the ion bombardment may have enhanced the surface diffusion of Cu atoms, but temperature effects are not yet confirmed separately from the resputtering effects by ion bombardment of relatively high energy and flux. Further study of temperature effects on filling characteristics is currently in progress.

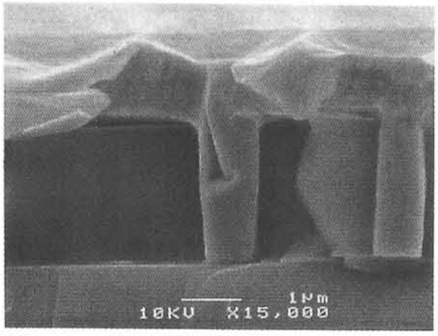


Fig. 10. Cross-sectional SEM image of a 1 μm diam contact hole filled at -300 V for 1 min and subsequently at -150 V for 2 min.

## 4. CONCLUSION

Highly ionized pure Cu ICP was successfully generated with the self-sustained sputter source and a single-turn antenna. ICP ionization increased the saturation ion current density at the substrate by a factor of 3-4. Effective sputter filling was achieved at dc substrate biases higher than 100 V. The possibility of complete filling of high aspect-ratio gaps by ICP ionized self-sputtering has been demonstrated.


## Acknowledgement

This work was supported by the Ministry of Education, Science, Sports, and Culture under Grant-in-Aid for Scientific Research on Priority Areas, "Ultimate Integration of Intelligence on Silicon Electronic Systems"(Head Investigator: Tadahiro Ohmi, Tohoku University).


### References


[1] S.M.Rossnagel, D.Mikalsen, H.Kinoshita, and J.J.Cuomo, J.Vac.Sci.Technol.A **9** (1991) 261.

[2] S.M.Rossnagel and J.Hopwood, J.Vac.Sci.Technol.**B12** (1994) 449.

[3] S.Shingubara, A.Sano, I.Utsunomiya, Y.Horiike, Z.J. Radzimski and W.M.Posadowski, Advanced Metallization for ULSI applications 1993, Mat.Res.Soc. Conf. Proc. ULSI-IX (1994) 87.

[4] W.M.Posadowski and Z.J.Radzimski, J.Vac.Sci.Technol.**A11** (1993) 2980.