Copper (Cu) interconnects have been applied to ultra large scale integrated circuits (ULSIs) to reduce the resistance of wiring and resistive-capacitive (RC) delay since the introduction of 130 nm complementary metal oxide semiconductors (CMOSs). As the feature size of trench and via continues to shrink, filling the gaps with Cu electroplating becomes more difficult. For perfectly gap filling, the opening of trench and via after the deposition of barrier and Cu seed have to be kept enough by thinning barrier and/or Cu seed. However, thinning Cu seed leads to Cu being agglomerated on the sidewall of both trench and via where Cu seed is too thin due to its poor coverage, resulting in the formation of voids inside trench and via. Therefore, one challenging issue for Cu interconnects is to fill trench and via completely without the agglomeration of Cu seed on the diffusion barrier layer.

New barrier metals that have better wettability with Cu than conventional Tantalum (Ta) have been studied to achieve continuous and smooth Cu film on them.1–26 Among them, Cobalt (Co) and Ruthenium (Ru) have been most frequently suggested for suppressing the agglomeration of Cu seed. Co is known to have the good film properties such as the low resistivity, the high melting point and the good adhesion with Cu. However, Co has the serious problems with chemical mechanical polishing (CMP) process and wet etching process. Co is corroded readily during CMP process and wet etching process, and the slits are occurred between Cu wiring and the interlayer dielectric. It results in the degradation of the device yield and reliability performance. As for Ru, the barrier property against Cu diffusion is not enough, and CMP process for Ru is a difficult technology and the slurry for CMP that had been developed for pure Ru was used in this experiment.

As the barrier layer against Cu diffusion, RuTa film was deposited by physical vapor deposition (PVD) method using Ru-Ta alloy target. The concentration of Ta in Ru-Ta alloy target used in this experiment was 10 at. %. RuTa(N) film which was doped with N in RuTa was deposited by PVD in a mixture of argon (Ar) and N2. Cu seed film was also deposited by PVD after the deposition of barrier film. In this experiment, Cu-Al alloy was used as a seed layer.31,32 The conventional Cu electroplating film was deposited and annealed to fill trench and via, and the wiring was formed by removing Cu and barrier on the field with CMP process. The slurry for CMP that had been developed for pure Ru was used in this experiment.

The film resistivity of RuTa and RuTa(N) was calculated with the thickness and the sheet resistance of the film measured by X-ray fluorescence (XRF) and 4-point probe, respectively. The concentration of Ta in Ru-Ta alloy and N in RuTa(N) was evaluated with X-ray photoelectron spectroscopy (XPS). The crystal orientation of RuTa and RuTa(N) film was investigated by using X-ray diffraction (XRD) with characteristic X-ray CuKα radiation. The wettability of Cu on the barrier film was investigated by observing the surface of the barrier layer with a scanning electron microscope (SEM) after 40 seconds of annealing at 350°C under Ar atmosphere. The oxidation resistance was investigated by observing the surface of the barrier film with a cross sectional transmission electron microscope (TEM) after 60 minutes of annealing at 250°C under air atmosphere.

The barrier property against Cu diffusion of Ru-Ta alloy was investigated with back-side secondary ion mass spectroscopy (SIMS) after 7 hours of annealing at 350°C which was almost equivalent to the back end of the line (BEOL) process in the thermal budget. The morphology of Cu seed on the barrier film was evaluated by observing trench after the deposition of barrier and Cu seed. The filling property with Ru-Ta alloy and RuTa(N) film which is doped with N in RuTa using fine Cu damascene structure have not been reported. In this paper, Ru-Ta alloy was applied as the diffusion barrier layer in fine Cu dual damascene interconnects, and the film property, filling property of Cu electroplating and reliability performances were investigated. The film which Nitrogen (N) was incorporated into Ru-Ta film was also evaluated, and the barrier structure for Ru-Ta alloy was considered on the basis of the film properties. The filling property of Cu electroplating, the electrical properties and the reliability performances with RuTa/RuTa(N) stacked barrier structure is mainly discussed.

**Experimental**

As the barrier layer against Cu diffusion, RuTa film was deposited by physical vapor deposition (PVD) method using Ru-Ta alloy target. The concentration of Ta in Ru-Ta alloy target used in this experiment was 10 at. %. RuTa(N) film which was doped with N in RuTa was deposited by PVD in a mixture of argon (Ar) and N2. Cu seed film was also deposited by PVD after the deposition of barrier film. In this experiment, Cu-Al alloy was used as a seed layer.31,32 The conventional Cu electroplating film was deposited and annealed to fill trench and via, and the wiring was formed by removing Cu and barrier on the field with CMP process. The slurry for CMP that had been developed for pure Ru was used in this experiment.

The film resistivity of RuTa and RuTa(N) was calculated with the thickness and the sheet resistance of the film measured by X-ray fluorescence (XRF) and 4-point probe, respectively. The concentration of Ta in Ru-Ta alloy and N in RuTa(N) was evaluated with X-ray photoelectron spectroscopy (XPS). The crystal orientation of RuTa and RuTa(N) film was investigated by using X-ray diffraction (XRD) with characteristic X-ray CuKα radiation. The wettability of Cu on the barrier film was investigated by observing the surface of the barrier layer with a scanning electron microscope (SEM) after 40 seconds of annealing at 350°C under Ar atmosphere. The oxidation resistance was investigated by observing the surface of the barrier film with a cross sectional transmission electron microscope (TEM) after 60 minutes of annealing at 250°C under air atmosphere.
using Ru-Ta alloy barrier was investigated with trenches of 45 nm in width with two conditions of Cu seed thickness, which was compared to that using the conventional Ta barrier.

For the evaluation of electrical property and reliability performances, a two-level Cu dual damascene structure fabricated with 45 nm node technology with chemical vapor deposition (CVD) based ultra low-k (ULK) dielectric was used. Via resistances with Ru-Ta alloy and Ta barrier were measured with Kelvin structure. The reliability performances with RuTa/RuTa(N) stacked barrier structure, including stress induced voiding (SIV) and electromigration (EM) were evaluated and compared to those with conventional Ta/TaN one. The failure analysis after EM stressed test was done with a cross sectional SEM. The effect of a physical etching during barrier deposition for digging analysis after EM stressed test was done with a cross sectional SEM. It is found that the concentration of deposited film is different from the composition of Cu seed thickness, which is due to the deposition condition of PVD or material of coil in the hardware. Figure 2 shows the film resistivity of RuTa and RuTa(N) as a function of flow rate of N₂ to Ar.

Results and Discussion

Film property of Ru-Ta alloy.—Figure 1 shows the film resistivity of RuTa and RuTa(N) with the thickness of 15 nm as a function of the flow rate of N₂ to Ar. The condition that the flow rate of N₂ to Ar is zero shows RuTa, and the others show RuTa(N). The resistivity of RuTa was about 60 μΩ·cm in width with two conditions of Cu seed thickness, which was compared to that using the conventional Ta barrier.

For the evaluation of electrical property and reliability performances, a two-level Cu dual damascene structure fabricated with 45 nm node technology with chemical vapor deposition (CVD) based ultra low-k (ULK) dielectric was used. Via resistances with Ru-Ta alloy and Ta barrier were measured with Kelvin structure. The reliability performances with RuTa/RuTa(N) stacked barrier structure, including stress induced voiding (SIV) and electromigration (EM) were evaluated and compared to those with conventional Ta/TaN one. The failure analysis after EM stressed test was done with a cross sectional SEM. The effect of a physical etching during barrier deposition for digging analysis after EM stressed test was done with a cross sectional SEM. It is found that the concentration of deposited film is different from the composition of Cu seed thickness, which is due to the deposition condition of PVD or material of coil in the hardware. Figure 2 shows the film resistivity of RuTa and RuTa(N) as a function of flow rate of N₂ to Ar.

Figure 1. Film resistivity of RuTa and RuTa(N) as a function of flow rate of N₂ to Ar.

The concentration of Ta in RuTa film was measured with 16 at. %. It is found that the concentration of deposited film is different from the composition of Cu seed thickness, which is due to the deposition condition of PVD or material of coil in the hardware. Figure 2 shows the concentration of N in RuTa(N) films as a function of flow rate of N₂ to Ar.

Figure 2. Concentration of N in RuTa(N) films as a function of flow rate of N₂ to Ar.

Ar. The concentration of N gradually increased from 4 at. % to 9 at. % with the increase of N₂, which indicates that N can be incorporated in RuTa(N) films by the deposition in a mixture of N₂ and Ar.

Figure 3 shows the XRD spectra of RuTa and RuTa(N). The thickness of barrier films is 15 nm. The condition that the flow rate of N₂ to Ar is zero shows RuTa, and the others show RuTa(N). XRD spectrum revealed that RuTa film strongly orientated to Ru(002). The lattice constant of Ru(002) in pure Ru is 2.11 Å. However, the lattice constant of Ru(002) in RuTa is calculated with 2.16 Å in the result of XRD. It is found that the addition of Ta into Ru shifts the lattice constant of Ru and has an impact on the crystal structure. The lattice misfit between Ru(002) and Cu(111) was lower than that of between Ta(110) and Cu(111). It suggests that RuTa has a good wettability to Cu(111) compared to Ta. Besides, Ta peaks were not confirmed in Figure 3. This is because Ta seems to be dispersed into Ru and Ta does not form an alloy with Ru under the concentration of Ta in Ru-Ta target used in this test. As for RuTa(N), the addition of N lowered the peak positions, which means that the lattice constant increases. As the increase of N₂, XRD peaks of RuTa(N) showed weaker and broader, and full width at half maximum (FWHM) of peaks became larger. It means that the addition of N₂ during deposition weakens the crystallinity of RuTa(N) films and the crystal size of the deposited films becomes smaller, which suggests that the barrier property against Cu diffusion of RuTa(N) is better than that of RuTa. Although N can be incorporated in RuTa(N) films by the deposition in a mixture of N₂ and Ar as shown in Figure 2, N does not form a strong bond with Ru or Ta due to the dispersion of Ta into Ru. Therefore, N seems to exist in non-equilibrium at RuTa grain boundaries while being deposited by PVD.

Figure 3. XRD spectra of RuTa and RuTa(N).

Figure 4 shows the SEM images of Cu on Ta, RuTa and RuTa(N) barrier films after 40 seconds of annealing at 350°C under Ar atmosphere. The thickness of each barrier metal films is 15 nm and that of Cu is 3 nm and 5 nm. In the case of Cu with 5 nm, Cu on all the barrier films was not agglomerated. Although the surface of Cu on Ta demonstrated agglomeration in the case of Cu with 3 nm, Cu on RuTa was not agglomerated. It means that the wettability of Cu on RuTa is much better than Cu on Ta. As for RuTa(N), the wettability of Cu on RuTa(N) film with the N₂/Ar flow ratio of 1.5 was excellent.

Figure 4. SEM images of Cu on Ta, RuTa and RuTa(N) after annealing.
However, the wettability of Cu on RuTa(N) with the N2/Ar flow ratio of 5.0 demonstrated agglomeration. This indicates that the wettability of Cu on RuTa(N) becomes poorer due to the increase of N content in RuTa(N) film and the degradation of crystallinity.

Figure 5 shows the cross sectional TEM images of Ta and RuTa films after 60 minutes of annealing at 250°C under air atmosphere. The thickness of Ta and RuTa is 30 nm. Oxide film which was considered as TaOx was formed on the surface of Ta after annealing. On the other hand, oxide film was not observed on the surface of RuTa. This result indicates that the oxidation resistance of RuTa is much better than that of Ta. Based on the result of oxidation resistance as shown in Figure 5, the wettability of Cu on Ta and RuTa was further evaluated to investigate the stability between Cu and barrier metal under the accelerated condition. After the deposition of Ta and RuTa with the thickness of 15 nm, the samples were exposed in the air once. Then, Cu film was deposited with the thickness of 5 nm on each barrier and annealed with 40 seconds at 250°C under Ar atmosphere. Figure 6 shows the SEM images of Cu on Ta and RuTa with air break. The surface of Cu on Ta demonstrated agglomeration. On the other hand, the surface of Cu on RuTa was not agglomerated. The wettability of Cu on Ta degrades due to the oxidation and that on RuTa keeps good even with exposure after the deposition of barrier film. Therefore, the interface between Cu and RuTa is more stable than that between Cu and Ta.

**Consideration of barrier structure for Ru-Ta alloy.**—The barrier structure for Ru-Ta alloy was considered on the basis of the film properties. As shown in Figure 7, RuTa/RuTa(N) stacked barrier structure is the most appropriate for Ru-Ta alloy. RuTa(N) film is deposited on dielectric film for the purpose of keeping the barrier property against Cu diffusion due to its poor crystallization. The N2/Ar flow ratio during the deposition of RuTa(N) film is decided to be 1.5 for keeping the good wettability of Cu as shown in Figure 4. After the deposition of RuTa(N), RuTa is deposited for the purpose of improving the wettability with Cu seed film.

The barrier property against Cu diffusion of RuTa/RuTa(N) stacked barrier structure was evaluated and compared to that of conventional Ta/TaN one. Figure 8 shows the schematic structure and method used for this evaluation of barrier property. Cu intensity in Ta/TaN and RuTa/RuTa(N) barrier films was measured by back side SIMS and the barrier property was evaluated by comparing Cu intensity in each barrier film. In order to remove the noise at the interface between Cu and barrier layer, the measuring point of Cu intensity was decided to be 5 nm far from Cu film and the distance between measuring point and Cu film was estimated with the thickness of barrier film and sputtering rate of SIMS.

Figure 9 shows the normalized Cu intensity in Ta/TaN and RuTa/RuTa(N) film after 7 hours of annealing at 350°C which is almost equivalent to the back end of the line (BEOL) process in the thermal budget. Normalized Cu intensity as deposition of barrier and Cu is also shown as a reference. Cu intensity in RuTa/RuTa(N) film was almost the same as that in Ta/TaN film. And, there was no difference of Cu intensity between as deposition and after annealing within the limits of measurement deviation. This means that Cu does not diffuse into barrier film even after annealing. Consequently, the barrier property of RuTa/RuTa(N) stacked barrier structure keeps the equivalent barrier property of conventional Ta/TaN one. In this regard, the barrier property could have been enhanced by the addition of Al in CuAl alloy seed. When Al atoms diffuse to the grain boundaries of barrier layer, they consume the oxygen in the film and form the AlOx easily due to the oxidation characteristic. It results in plugging the grain boundaries against Cu diffusion and enhancing the barrier property.

Figure 10 shows the cross sectional SEM images of trenches after the deposition of barrier and Cu seed for the evaluation of the morphology of Cu film inside trenches. The thickness of Ta/TaN and RuTa/RuTa(N) is 7.5/7.5 nm, and that of Cu seed is 20 nm. The surface...
morphology of Cu seed on conventional Ta/TaN barrier seemed to be agglomerated. On the other hand, Cu seed on RuTa/RuTa(N) stacked barrier structure seemed very smooth and not to be agglomerated.

Figure 11 shows the cross sectional SEM images of 45 nm wide trenches after filling with Cu electroplating for the comparison of the filling property between Ta/TaN and RuTa/RuTa(N) barrier. The thickness of Ta/TaN and RuTa/RuTa(N) is 7.5/7.5 nm, and that of Cu seed is 20 nm and 30 nm. As for the condition of Cu seed with 30 nm, voids were occurred inside trenches with both Ta/TaN and RuTa/RuTa(N) barrier. This is attributed to the overhang at the opening of trenches due to thick Cu seed. Therefore, the thickness of Cu seed was reduced to 20 nm for keeping enough opening of trenches. Using Ta/TaN barrier and Cu seed with 20 nm, trenches couldn’t be filled completely with Cu electroplating and no Cu film grew inside trenches. This result indicates that Cu seed on Ta/TaN is agglomerated and become discontinuous on the sidewall of trenches as shown in Figure 10. On the other hand, trenches using RuTa/RuTa(N) barrier and Cu seed with 20 nm could be completely filled without voids. This indicates that Cu seed even with the thickness of 20 nm on RuTa/RuTa(N) can keep continuous film on the sidewall of trenches, and the filling property of Cu electroplating can be improved by using RuTa/RuTa(N) stacked barrier structure.

Electrical property and reliability performance.—Figure 12 shows the schematic structure for evaluations of electrical property and reliability performances. In this test, a two-level Cu dual damascene structure fabricated by 45 nm node technology with CVD based ULK dielectrics was used. RuTa/RuTa(N) stacked barrier structure was applied to the upper metal layer (M2). Conventional Ta/TaN stacked barrier structure was also applied to M2 for a reference. Only Ta/TaN barrier structure was applied for the lower metal layer (M1). For investigating the effect of the via bottom shape, the physical etching during barrier deposition for digging into via bottom was applied.

Figure 13 shows the via resistance measured with Kelvin structure which the width of M1 trench and M2 trench are 70 nm and the diameter of V1 via is also 70 nm. The via resistance of the type of flat via bottom with RuTa/RuTa(N) was much lower than that with conventional Ta/TaN. This is because the resistivity of RuTa/RuTa(N) is about three times lower than that of Ta/TaN. Via resistance with conventional Ta/TaN was dramatically reduced by digging via bottom. On the other hand, the via resistance of the type of flat via bottom with RuTa/RuTa(N) was almost the same as that of digged via bottom. This result is attributed to the low resistivity of RuTa and RuTa(N).

Figure 14 shows the ratio of via-chain resistance between before and after 500 hours of annealing at 200 °C. This result shows the SIL reliability performance. The structure used in this test is that the width of M1 trench and M2 trench are 210 and 5000 nm respectively, and the diameter of V1 via is 70 nm. Ratio of via-chain resistance of all the conditions was almost the same. Therefore, SIL reliability performance with RuTa/RuTa(N) barrier is excellent and equivalent with conventional Ta/TaN barrier. SIL performance has no remarkable difference between flat via bottom and digged via bottom. This indicates that SIL performance is improved due to Cu-Al alloy seed.32

The lifetime for via EM is shown in Figure 15. The width of M1 trench is 210 nm and that of M2 trench is 70 nm, and the diameter of V1 via is 70 nm. The direction of current is up-stream. EM test was done under the condition of the temperature with 300 °C and the current with 0.15 mA/via. The failure criterion was that the ratio of resistance before and after EM test was over 10%. The mean time to failure (MTF) had no difference between RuTa/RuTa(N) and Ta/TaN barrier structure. However, the failure time with RuTa/RuTa(N) barrier structure showed the tight distribution compared to that with Ta/TaN one. This result indicates that the estimated life time with RuTa/RuTa(N) barrier structure is much longer than that of Ta/TaN.
one. It is found that the reliability performance of via EM is improved by using RuTa/RuTa(N) stacked barrier structure.

To investigate the difference of distribution between RuTa/RuTa(N) and Ta/TaN barrier structures, the failure analysis after EM stressed test was done. The result of the failure analysis is shown in Figure 16. The failures with the mode of RuTa/RuTa(N) and the long-life mode of Ta/TaN were attributed to the formation of voids in the upper trench (M2). On the other hand, the failure with the short-life mode of Ta/TaN was due to the formation of voids in via (V1). This result indicates that the thin Cu seed on Ta/TaN barrier is agglomerated and become discontinuous film on the sidewall of via where the coverage of barrier and Cu seed is poor, and resulting in the degradation of filling property in via. It follows that the voids in via occur and cause the wide distribution of failure time for conventional Ta/TaN barrier structure. On the other hand, Cu seed on RuTa/RuTa(N) stacked barrier structure in via is really smooth and keeps continuous, and the filling property for via is excellent. It results in the tight distribution of failure time for RuTa/RuTa(N) stacked barrier structure.

**Conclusions**

Ru-Ta alloy was investigated as the diffusion barrier layer in Cu dual damascene interconnects, and the film which N was incorporated into Ru-Ta film was evaluated. The resistivity of RuTa and RuTa(N) film were less than half that of Ta. RuTa film strongly orientated to Ru (002). The misfit between Ru(002) and Cu(111) was lower than that between Ta(110) and Cu(111). Therefore, the wettability of Cu seed on RuTa was much better than that on Ta. The barrier property against Cu diffusion of RuTa/RuTa(N) stacked barrier structure kept the equivalent barrier property of conventional Ta/TaN one. The perfect filling of 45 nm wide trenches was achieved with RuTa/RuTa(N) stacked barrier due to the suppression of the agglomeration of Cu seed on the
sidewall of trenches. Via resistance with Ru-Ta alloy barrier was much lower than that with Ta one due to its low resistivity. The estimated lifetime of via EM with RuTa/RuTa(N) stacked barrier was longer than that of conventional Ta/TaN one because of the good wettability and the filling property in via. Consequently, Cu filling property and reliability performance can be improved with RuTa/RuTa(N) stacked barrier structure in Cu interconnects.

Acknowledgments

This work was supported by Applied Materials Japan Inc. and Applied Materials Inc. for providing the information about Ru-Ta alloy. The authors acknowledge Dr. Shigeki Zaima of Nagoya University for fruitful discussions on this paper.

References

1. H. Kim and Y. Shimogaki, *Proc. of Advanced Metallization Conference 2004*, p. 551 (2004).
2. O. K. Kwon, S. H. Kwon, H. S. Park, and S. W. Kang, *J. Electrochem. Soc.*, 151(12), C753 (2004).
3. Y. Matsu, M. Hiratani, T. Nabatame, Y. Shimamoto, and S. Kimura, *Electrochemical and Solid-State Letters*, 5(1), C18 (2002).
4. R. Chan, T. N. Arunagiri, T. Zhang, O. Chyan, R. M. Walance, M. J. Kim, and T. Q. Hur, *Electrochemical and Solid-State Letters*, 7(8), G154 (2004).
5. H. Kim, T. Koseki, T. Obha, T. Ohta, Y. Kojima, H. Sato, and Y. Shimogaki, *J. Electrochem. Soc.*, 157, G594 (2005).
6. M. Damayanti, T. Sritiran, Z. H. Gan, S. G. Mhaisalkar, N. Jiang, and L. Chanb, *J. Electrochem. Soc.*, 153, 6, 341 (2006).
7. A. Sakata, S. Yamashita, S. Otomo, M. Hatano, J. Wada, K. Higashi, H. Yamaguchi, T. Yoshio, K. Imamizu, M. Yamada, M. Hasunuma, S. Takahashi, A. Yamada, T. Hasegawa, and H. Kaneko, *Proc. of International Interconnect Technology Conference 2006*, pp. 101 (2006).
8. X. P. Qu, J. J. Tan, M. Zhou, T. Chen, Q. Xie, G. P. Ru, and B. Z. Li, *Applied Physics Letters*, 88, 151912 (2006).
9. M. Damayantia, T. Sritiran, S. G. Mhaisalkar, and Z. H. Gan, *Applied Physics Letters*, 88, 044101 (2006).
10. S. Ogawa, N. Tarumi, M. Abe, M. Shiohara, H. Imamura, and S. Kondo, *Proc. of International Interconnect Technology Conference 2008*, pp. 102 (2008).
11. M. Tagami, N. Furutake, S. Saito, and Y. Hayashi, *Proc. of International Interconnect Technology Conference 2008*, pp. 205 (2008).
12. N. Tarumi, N. Oda, S. Kondo, and S. Ogawa, *Proc. of International Interconnect Technology Conference 2009*, pp. 203 (2009).
13. H. Y. Huang, C. H. Hsieh, S. M. Jeng, H. J. Tao, M. Cao, and Y. J. Mii, *Proc. of International Interconnect Technology Conference 2010*, pp. 1 (2010).
14. A. P. McCoy, J. Bogan, C. Byrne, P. Casey, J. G. Lozano, P. D. Nellist, and D. Hughes, *Proc. of International Interconnect Technology Conference 2014*, pp. 273 (2014).
15. C. W. Cheng, J. S. Chen, and J. S. Jeng, *J. Electrochem. Soc.*, 155(12), H1003 (2008).
16. C. W. Cheng, J. S. Jeng, and J. S. Chen, *J. Electrochem. Soc.*, 157(11), H997 (2010).
17. S. P. Ding, Q. Xie, S. Mueller, T. Waechtler, H. S. Lu, S. E. Schulz, C. Detavernier, X. P. Qu, and T. Gessner, *J. Electrochem. Soc.*, 158(12), H1228 (2011).
18. J. S. Fang, J. H. Lin, B. Y. Chen, and T. S. Chiu, *J. Electrochem. Soc.*, 158(2), H97 (2011).
19. C.-C. Yang, T. Spooner, S. Ponoth, K. Chanda, A. Simon, C. Lavoie, M. Lane, C.-K. Hu, E. Liniger, L. Gignac, T. Shaw, S. Cohen, F. McFeely, and D. Edelstein, *Proc. of International Interconnect Technology Conference 2006*, pp. 187 (2006).
20. M. Abe, M. Ueki, M. Tada, T. Omdera, N. Furutake, K. Shimura, S. Saito, and Y. Hayashi, *Proc. of International Interconnect Technology Conference 2007*, pp. 4 (2007).
21. C. W. Cheng, J. S. Chen, and J. S. Jeng, *J. Electrochem. Soc.*, 155(6), H438 (2008).
22. C. C. Chang and F. M. Pan, *J. Electrochem. Soc.*, 158(4), G097 (2011).
23. C. Y. Wu, Y. S. Wang, and W. H. Lee, *J. Electrochem. Soc.*, 159(11), D684 (2012).
24. S. Armini, Z. El-Mekki, K. Vandersmissen, H. Philippsen, S. Rodet, M. Honore, A. Radisce, Y. Civale, E. Beyne, and L. Leunissen, *J. Electrochem. Soc.*, 158(2), H160 (2011).
25. M. He, X. Zhang, T. Nogami, X. Lin, J. Kelly, H. Kim, T. Spooner, D. Edelstein, and L. Zhao, *J. Electrochem. Soc.*, 160(12), D3040 (2013).
26. Q. Huang, B. C. Baker-O’Neal, C. Cabral Jr., E. Simonyi, V. R. Deline, and M. Hopstaken, *J. Electrochem. Soc.*, 160(12), D3045 (2013).
27. H. Wojcik, M. Junige, W. Bartha, M. Albert, V. Neumann, U. Merkel, A. Peeva, J. Gluch, S. Menzel, F. Munnik, R. Liske, D. Utes, I. Richter, C. Klein, H. J. Engelmann, P. Ho, C. Hossbach, and C. Wenzel, *J. Electrochem. Soc.*, 159(2), H662 (2012).
28. C. Yang, S. Cohen, T. Shaw, P. C. Wang, T. Nogami, and D. Edelstein, *Proc. of Electron Device Letters 2010*, pp. 722 (2010).
29. H. Wojcik, R. Kaltofen, U. Merkel, C. Krien, S. Strehle, J. Gluch, M. Knaut, C. Wenzel, A. Preuse, JW Barth, M. Geidel, B. Adolphi, V. Neumann, R. Liske, and F. Munnik, *Microelectronic Engineering*, 92, 71 (2012).
30. S. Armini, Z. El-Mekki, M. Nagar, A. Radisce, and P. M. Vereeken, *J. Electrochem. Soc.*, 161(10), D564 (2014).
31. P. Wang, S. P. Murarka, D. A. Kaminski, S. Bedell, and W. A. Lanford, *J. Electrochem. Soc.*, 148(9), G481 (2001).
32. K. Mori, K. Maekawa, N. Amou, D. Kodama, H. Miyazaki, N. Suzumura, K. Honda, Y. Hirose, K. Asai, and M. Yoneda, *Proc. of Advanced Metallization Conference 2006*, pp. 407 (2006).