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NUMERICAL SIMULATION OF THE EFFECTS OF DIFFERENT COATINGS ON GRAPHITE SUSCEPTOR

FOR THE INDUCTION PROCESS OF POLYCRYSTALLINE SILICON

K. L. Lian[1,a], S. S. Lian[2,b], and S. Tsao[3,c]

[1.] Department of Electrical Engineering, NTUST, Taipei, Taiwan, R. O. C.

[2] Department of Materials Science and Engineering, NTU, Taipei, Taiwan, R. O. C.

[3] Materials and Chemical Engineering Lab, ITRI, Chu Tung, Hsin Chu, Taiwan, R. O. C.

Keywords: Vacuum induction melting, Susceptor, Polycrystalline silicon, Coating

Abstract. The vacuum induction melting and control solidification is a new developed process for the manufacture of polycrystalline silicon with the advantage of quick heating rate compared to the traditional resistance heating method. The graphite susceptor of the induction furnace plays a key role in controlling the temperature of the melt of polycrystal silicon for solar cells. This paper investigates how different coatings painted on the susceptor would influence the heating efficiency and the temperature distribution of the silicon melt. A graphite susceptor is usually coated with a thin film of insulating material to reduce heat losses and to prevent vapors such as SiO to contaminate the susceptor. Numerical simulations show that the coating material at the outer surface of the susceptor should be the one with low thermal conductivity to prevent heat loss. On the other hand, the coating on the inner surface should be the material with high thermal conductivity to allow easy heat transfer.

Introduction

The photovoltaic solar energy is non-toxic and environmental friendly. It is also inexhaustible in supply and has been considered as one of the important green energy in the 21st century. In general, photovoltaic cells can be classified into three types - single crystal, polycrystalline, and amorphous silicon. Among them, polycrystalline silicon wafer occupies over 50% in the solar energy market [1], because the production cost is lower compared to the single crystal silicon and its efficiency is higher than that of the amorphous silicon. Its growth methods include directional casting [2], heat exchanger method (HEM) and electromagnetic casting method [1]. The vacuum induction melting and control solidification [3] is a new developed process for the manufacture of polycrystalline silicon with the advantage of quick heating rate compared to the traditional resistance heating method [4]-[6]. However, whether this process could provide the same uniform temperature distribution as the widely used HEM, is something needed to be thoroughly studied and investigated. Moreover, the parameters of the induction melting furnaces in general, can influence the success and efficiency of the melting of the silicon ingot. Improper choices of these parameters may result in incomplete melting of the silicon ingot. Experimental studies on the induction melting of a crystal casting furnace is expensive due to high material costs and the fact that the growth of the polycrystalline silicon takes a long time to be completed. Therefore, it is more practical and economical to employ numerical simulation to find the systematic relationship between the processing parameters and temperature distribution in the furnace.

Although research work has been contributed to the simulation of single crystal growth [4], [7], [8], fewer studies have been carried out on the simulation process of induction melting of silicon in the induction melting furnace [9]. A simulation of the induction melting process was conducted in our previous work [6] to investigate how to melt and grow polycrystalline silicon successfully in an induction melting furnace. In that study, the focus was to investigate on how the withdraw rate and conductor positions relate to the growth of the polycrystalline. In the work of [10], how electrical conductivity and thickness of the graphite susceptor influencing the temperature distribution of the silicon melt was studied. This paper essentially extends the work of [10] to investigate how different coatings painted on the susceptor would influence the heating efficiency and the temperature distribution of the silicon melt. This study is important because a graphite susceptor is usually coated with a thin film of insulating material to reduce heat losses and to prevent vapors such as SiO to contaminate the susceptor. Knowing what type of coating leads to the best heating efficiency and temperature distribution can help engineers to design the optimal induction furnace.

Numerical Simulation

The axis-symmetric vacuum induction melting furnace for the polycrystal growth is shown in Fig. 1. The furnace components are made of several material including silicon (crystal and melt), quartz (crucible), graphite (susceptor and container), CrNi steel (cooling base-plate and furnace wall), and copper (windings). The furnace operates based on the principles of induction heating. An ac current, passing through the windings, creates alternating magnetic fields, and heat is generated inside the graphite susceptor due to the induced eddy currents [11]. Silicon ingot is melted due to the heat transfer (conduction, convection and radiation). The overall process is nonlinear and involves coupling among thermal, electromagnetic, and hydrodynamic phenomena. Thus, the commercial software CGSim, able to account for this coupling effect was used for the simulation.

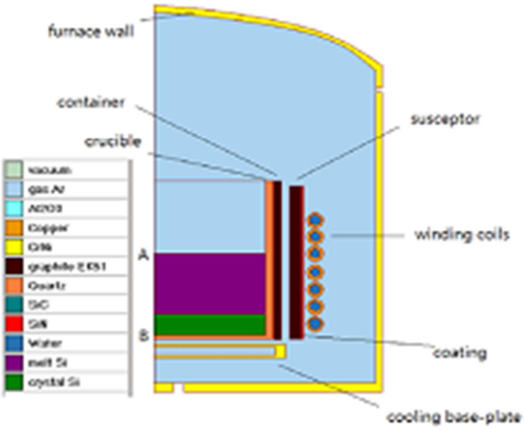


Figure 1: The geometry of the vacuum induction melting furnace.

Results and Discussions

A thin film of coating painted at the outer surface of the graphite susceptor

To investigate how different coating painted at the outer surface (see Fig. 1) of the graphite susceptor, a thin film of Al2O3, SiC, and Si3N4 were painted respectively on the susceptor.

Figs. 2, 3, and 4 show the simulated temperature distribtuion of the silicon when they are painted on the outer surface of the graphite susceptor.

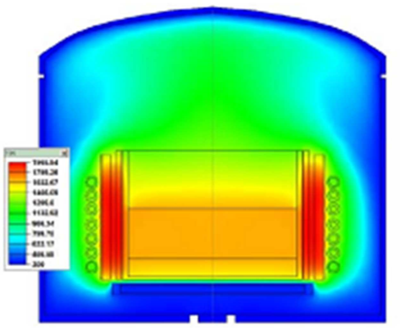


Figure 2: The temperature distribution when a thin film of Al2O3 is painted on the outer surface of the graphite susceptor.

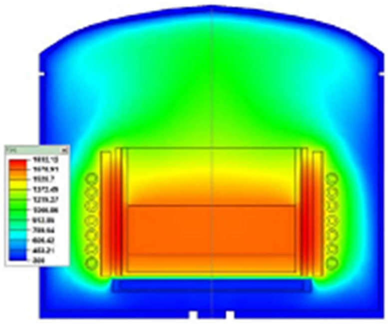


Figure 3: The temperature distribution when a thin film of SiC is painted on the outer surface of the graphite susceptor.

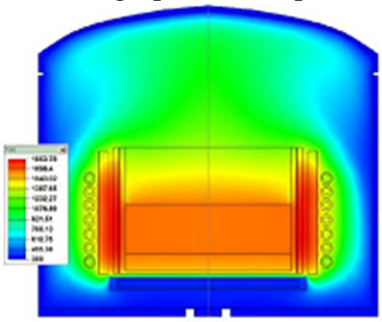


Figure 4: The temperature distribution when a thin film of Si3N4 is painted on the outer surface of the graphite susceptor.

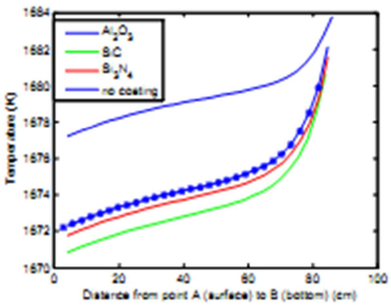


Figure 5: The temperature of the silicon melt vs. the distance from point A to B of Fig. 1.

Fig. 5 shows how the temperature varies from point A, which is close to the melting surface, to point B, which is at the bottom of the crucible (see Fig. 1). As can be noted, the Al2O3 coating yields the best heating efficiency as the overall silicon melt temperature is higher than the other two cases (coatings of SiC and Si3N4). Since the thermal conductivity of Al2O3 is lower than those of Si3N4 and SiC, a thin film made of Al2O3 coated at the outer surface of the suceptor can effectively prevent from heat losses. On the other hand, the thermal conductivities of SiC and Si3N4 are relatively high. Hence, coating the susceptor with these two material increases heat flow, yielding lower temperature melt.

A thin film of coating painted at the inner surface of the graphite susceptor

To investigate how different coating painted at the inner surface (see Fig. 6) of the graphite susceptor, a thin film of Al2O3, SiC, and Si3N4 were painted respectively on the susceptor. Figs. 7, 8, and 9 show the simulated temperature distribtuion of the silicon when they are painted on the inner surface of the graphite susceptor.

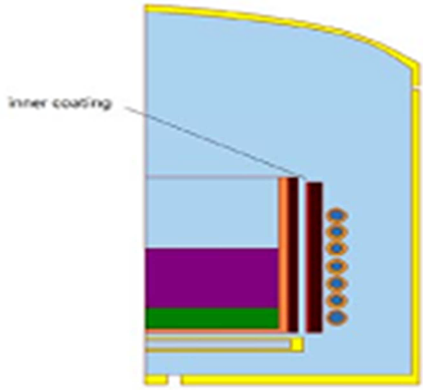


Figure 6: The inner surface of the graphite susceptor is painted with a thim film of coating.

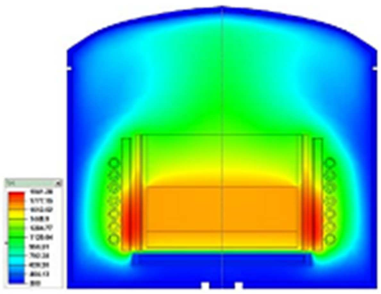


Figure 7: The temperature distribution when a thin film of Al_2O_3 is painted on the inner surface of the graphite susceptor.

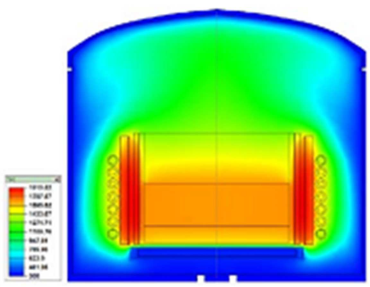


Figure 8: The temperature distribution when a thin film of SiC is painted on the inner surface of the graphite susceptor.

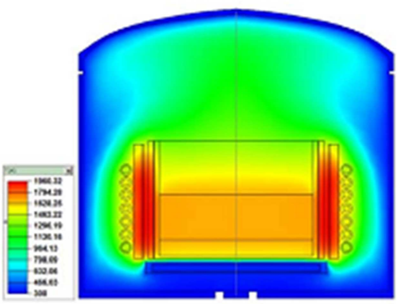


Figure 9: The temperature distribution when a thin film of Si_3N_4 is painted on the inner surface of the graphite susceptor.

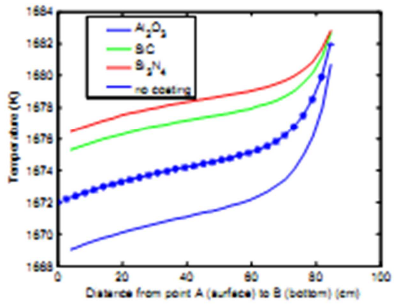
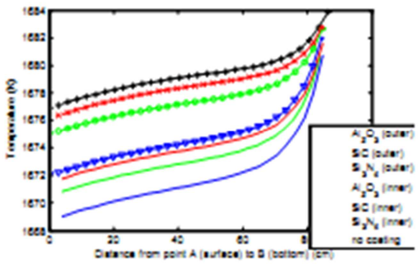


Figure 10: The temperature of the silicon melt vs. the distance from point A to B of Fig. 1.

Fig. 10 shows how the temperature varies from point A, which is close to the melting surface, to point B, which is at the bottom of the crucible (see Fig. 1). As can be noted, the Si3N4 coating yields the best heating efficiency as the overall silicon melt temperature is higher than the other two cases (coatings of Al2O3 and SiC).
Different from the cases of the outer surface, better heating efficiency can be achieved when the inner surface is coated with a thin film of high thermal-conductivity material such as Si3N4 and SiC. This is because the heat can be easily transferred to the silicon melt.

When combining Fig. 5 and Fig. 10 to compare the temperature profiles of these seven cases, one sees that a graphite susceptor whose outer surface is coated with Al2O3 yields the highest temperature of the melt whereas a inner surface coating of Al2O3 would yield the lowest temperature for melt. The second and third best heating efficiency were achieved by the inner surface coating made of Si3N4 and SiC, respectively. This is because they have high thermal conductivity, yielding more heat to transfer to the silicon melt.



Summary

Observed from the simulation results, one can draw the following conclusions:

• The type of the coating material and the position of the coating on the graphite susceptor have great influence on the temperature distribution.

• In general, the coating material on the outer surface of the suceptor should be the one with low thermal conductivity to prevent heat losses.

• On the other hand, the coating material on the inner surface of the suceptor should be the one with high thermal conductivity to allow heat easily transfer to the silicon.

Acknowledgment

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References

[1] A. K. Søiland, Silicon for solar cells, Ph.D. Thesis, Norwegian University of Science and Technology (NTUN), Trondheim, Norway, 2004.

[2] K. Fujiwara, W. Pan, N. Usami, K. Sawada, M. Tokairin, Y. Nose, A. Nomura, T. Shishido, K. Nakajima, "Growth of structure-controlled polycrystalline silicon ingots for solar cells by casting", Acta Materialia 54 (2006), pg. 3191-3197.

[3] A. Bermúdez, D. Gómez, M. C. Muñiz, P. Salgado and R. Vázquez, "Numerical Simulation of Induction Furnaces for Silicon Purification", Mathematics in Industry, 2008, Vol. 12, pg. 48-65.

[4]T. Munakata, S. Someya, and I. Tanasawa, "Three-dimensional CZ silicon melt flow under induction heating," Journal of Crystal Growth, Vol. 275 (2005), Pages: e1565-e1569.

[5] T. Munakata and I. Tanasawa, "Study on silicon melt convection during the RF-FZ crystal growth process: I. experimental flow visualization," Journal of Crystal Growth, Vol. 206 (1999), Pages 23-26.

[6] S. S. Lian, Y. S. Wang and S. Tsao, "Simulation of Melting Process of Silicon in a Vacuum Induction Polycrystal Growth Melting Furnace," 23rd European Photovoltaic Solar Energy Conference, September 1-5, 2008, Valencia, Spain, Pages 385-389.

[7] T. Munakata, S. Someya, and I. Tanasawa, "Effect of high frequency magnetic field on CZ silicon melt convection," International Journal of Heat and Mass Transfer, 47(2004), Pages: 4525-4533.

[8] V. V. Kalaeva, D. P. Lukanina, V. A. Zabelina, Y. N. Makarov, J. Virbulisc, E. Dornbergerc and W. von Ammon, "Calculation of bulk defects in CZ Si growth: impact of melt turbulent fluctuations," Journal of Crystal Growth, 250 (2003), Pages: 203-208.

[9] S Servanta, B Pillinb, D Sartia and F Durandb, "Grain structure of silicon solidified from an inductive cold crucible," Materials Science and Engineering: A-173 (1993), Pages 63-66.

[10] Y. H. Chen, S. C. Chu, K. L. Lian, S. S. Lian, and S. Tsao, "Investigation of the Effects of Parameters of Graphite Susceptor and Base Plate for Melting Process of Polycrystalline Silicon," 25th EU PVSEC / WCPEC-5, 6-10 September, 2010, Valencia, Spain

[11] V. Rudnev, D. Loveless, R. Cook, and M. Black, Handbook of Induction Heating, Taylor & Francis, 2003.