COLD CRUCIBLE CZOCHRALSKI FOR SOLAR CELLS

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INTRODUCTION

The efficiency and radiation resistance of present silicon solar cells are a function of the oxygen and carbon impurities and the boron doping used to provide the proper resistivity material. The standard Czochralski (CZ) process used to grow single crystal silicon contaminates the silicon stock material due to the use of a quartz crucible and graphite components. The use of a process which replaces these elements with a water cooled copper to crucible has provided a major step in providing gallium doped (100) crystal orientation, low oxygen, low carbon, silicon. This paper provides a discussion of the Cold Crucible Czochralski (C^3Z) process and recent Float Zone (FZ) developments.

PROGRAM GOALS

The goal of this program is to provide high efficiency, low cost, radiation resistant solar cells by providing high purity, low dislocation count, single crystal silicon. The two major impurities to be removed are carbon and oxygen with a maximum concentration of $1x10^{12}$ for oxygen and $5x10^{16}$ for carbon. Minority carrier lifetime should be 100 microseconds or greater for 1 ohm-cm material. Solar cell performance goals are 18% efficiency (AMO) at 25°C with 15% end of life efficiency at 25°C after exposure to an electron fluence of $1x10^{15}$ e/cm^2 at 1 MeV.

APPROACH

The standard Czochralski method is a well proven process for growing several million kilograms of silicon a year. The major drawback of this process is due to the contamination of the melt from the quartz crucible. The crucible contributes boron, aluminum, phosphorous and oxygen contaminants to the melt along with other minor constituents. The Cold Crucible Czochralski (C^3Z) eliminates this problem by replacing the quartz crucible with a water cooled copper crucible (fig. 1). A very pure silicon charge is placed in the copper crucible and subsequently heated using a susceptor. Once the silicon begins to melt, the RF field couples into the silicon to complete the melt. The RF field then levitates the silicon away from the water cooled fingers as shown in figure 2. A seed crystal is brought in contact with the surface of the melt, and after adhering to the liquid silicon, the rotating crystal is drawn up out of the melt and the single crystal silicon allowed to solidify. The (100) crystal growth is based upon the orientation of seed crystal. The diameter and dislocation count are a function of the thermodynamic exchanges between the single crystal rod, the turning and pulling rate and the frequency and power in the RF field.

PROGRESS

As early as September 1980, moderate success in growing a 1" diameter (100) single crystal was achieved. It was approximately 1800 ohm-cm p-type that twinned in the neck region, producing an orientation slightly off (111). Maximum dislocation densities were about $5x10^4/cm^2$ in the center and $6x10^5$ at the edge. Dislocation densities were further reduced to $5x10^4/cm^2$ at the edge and as low as $6x10^2/cm^2$ at the center of the seed end. Dislocations are linear imperfections in crystal lattices associated with extraneous, missing or warped planes of atoms. The program is oriented toward the growth of three resistivities, 0.1, 1.0 and 10.0 ohm-cm so that gallium doped pure silicon can be properly evaluated. Initial attempts to grow 10 ohm-cm material resulted in an 8 ohm-centimeter crystal with a resistivity variation of +3, -6% over a 5 cm long crystal. Refinements in the crystal growth process made it possible to more accurately dope the crystals on subsequent runs.

Recently, 3 crystals of 2.54 cm diameter were grown from a 350 gm charge in 2.5 cm to 3.3 cm lengths. Good single crystals were grown at resistivities of 700 ohm-cm and 1500 ohm-cm (p-type).

Presently, wafers sliced from 0.1, 1.0 and 10 ohm-centimeter material are being made into solar cells. Additional wafers are being analyzed by FTIR to determine the amount of oxygen, carbon and gallium in the material. Table 1 shows two typical gallium doped wafers which are presently being evaluated.

Recently, studies have been conducted with single pass FZ and regular CZ silicon material made into N+/P solar cells. Low resistivity cells made with boron or gallium doping were irradiated at a fluence of $1x10^{14}$ e/cm^2 at 1 MeV and exposed to photon radiation for 10 hours. For the 2 ohm-centimeter boron doped solar cells, P/P_o was 0.728, for the gallium doped cells it was 0.818 which confirms the fact that gallium doped pure silicon is better than boron doped silicon.

FUTURE WORK

Although it was possible to make 2.54cm diameter C^3Z silicon, hardware problems caused by RF arcing, hardware design, and other system unknowns caused reconsideration of redesigning the system for 6.3cm diameter silicon. During the past year, an AFWAL Material Laboratory Manufacturing Technology program to Hughes Industrial Products Division has resulted in the ability to manufacture vacuum FZ in large quantities at reduced costs. This success spurred an effort to replace C^3Z by 3 pass FZ and start with extremely pure polysilicon rods costing upwards of $750 per kilo. From this material 0.1, 1.0 and 10 ohm-cm (100) crystals will be grown.

Wafers will be analyzed by conventional methods to determine oxygen and carbon content, gallium distribution, dislocation count, resistivity, mobility and radiation damage. Solar cells made from additional wafers will be characterized using IV curves and will be subsequently radiation tested at fluences up to $1x10^{15}$ e/cm^2 at 1 MeV.

CONCLUSIONS

The gallium doped C^3Z or FZ material could be a mission enabling technology. Gallium arsenide solar cells with 17% to 18% BOL efficiencies will not be available in production quantities until the 1985-1986 time period. Until then, the 13.5% efficient silicon solar cell with a 9% EOL efficiency due to radiation damage cannot be expected to provide the longer life in high radiation orbits without costly replacement of satellites.

REFERENCES

1. Investigation of High Purity Czochralski Grown Silicon for Solar Cell Applications, Air Force Contract F33615-81-C-2025, Spectrolab, Sylmar CA. Principal Investigator: William Taylor.

2. "Growth of High Purity Oxygen-Free Silicon by Cold Crucible Techniques" Air Force Contract F-19628-80-C-0104, Ceres Corp, Waltham MA. Principal Investigator: Joseph F. Wenkus.

3. Solar Cell Radiation Handbook. JPL publication 77-56. Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA.

4. Low Resistivity - High Lifetime Single Crystal Silicon Investigation F33615-77-C-2045 Spectrolab, Sylmar CA. Principal Investigators J. Fodor and R. W. Opjorden.

TABLE 1

COLD CRUCIBLE GROWN CRYSTALS

Crystal No.	CC 814901	CC 815001
Nominal Resistivity	1.0 ohm-cm	10 ohm-cm
Type	p	p
Dopant	Ga	Ga
Growth Date	12-9-81	12-18-81
Polysilicon Lot	CB021199	CB021199
Poly Data:		
Boron	.06 ppb	.06 ppb
Donors	.25 ppb	.25 ppb
Crystal Diameter	0.6 inches	0.3 to 0.8 inches
Length (Approx.)	2.7 inches	1 inch
Resistivity vs. Distance From Seed (cm)		
1	.951 ohm-cm	11.7 ohm-cm
2	.848	12.6
3	.856	
Dislocation Density	(to be determined)	

COLD CRUCIBLE CZOCHRALSKI STARTUP

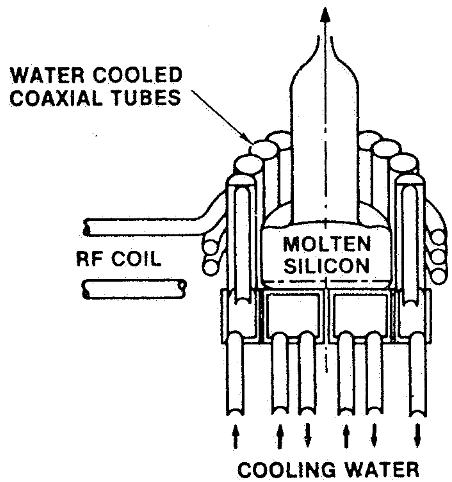

Figure 1

COLD CRUCIBLE CZOCHRALSKI CRYSTAL GROWTH

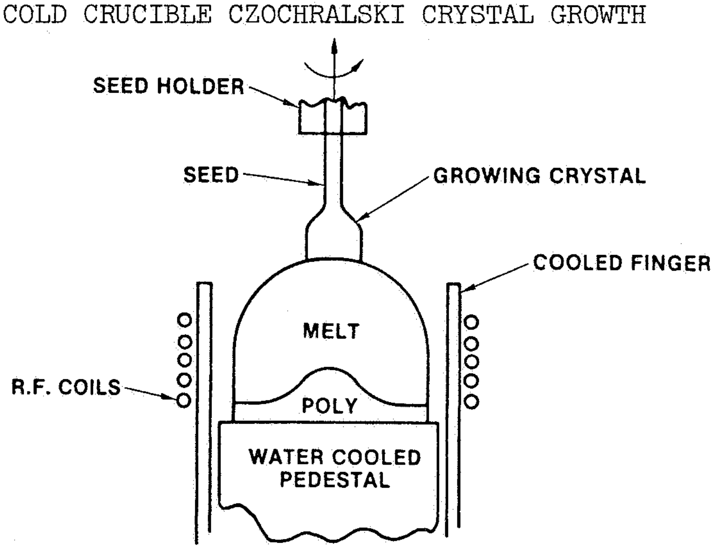

Figure 2