N86-29355

CRYSTAL GROWTH FOR HIGH-EFFICIENCY SILICON SOLAR CELLS WORKSHOP: SUMMARY

JET PROPULSION LABORATORY

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Workshop Objectives

- **Review the state of the art in the growth of silicon crystals for high-efficiency solar cells**
- **Define sheet requirements for high-efficiency solar cells**
- **Identify future areas of research**

Presentation Outline

- **Session contents**
- **Technical highlights**
- **Conclusions**
- **Future areas of research**

Session Contents

Session I:

Material Requirements for High-Efficiency Silicon Solar Cells

Martin Wolf (University of Pennsylvania)

The Status of Silicon Ribbon Growth Technology for High-Efficiency Solar Cells

Ted Ciszek (Solar Energy Research Institute)

Future Application of Czochralski Pulling for Silicon

John Matlock (SEH America)

Potential Productivity Benefits of Float-Zone vs Czochralski Crystal Growth

Takao Abe (SEH)

Session II:

A New Outlook on Control of Crystalline and Chemical Perfection During Growth of Silicon

August Witt (Massachusetts Institute of Technology)

MCz: Striations in Cz Silicon Crystals Grown Under Various Axial Magnetic Field Strengths

George Kim (IBM)

High-Purity, Low-Defect FZ Silicon

Hiroshi Kimura and Glen Robertson (Hughes Research Laboratories)

Defects in Silicon Effect on Device Performance and Relationship to Crystal Growth Conditions

Lubek Jastrzebski (RCA Laboratories)

Session III:

Simulation of the Temperature Distribution in Crystals Grown by Czochralski Method

Milorad Dudukovic (Washington University)

Convective Effects in Float-Zone and Czochralski Melts

Paul Neitzel (Arizona State University)

Session IV:

Thermal-Capillary Models of Meniscus-Defined Crystal Growth: Interactions of Melt/Solid and Melt/Gas Interfaces with Crystal Size

Robert Brown (Massachusetts Institute of Technology)

Impurities in Silicon Solar Cells

Richard Hopkins (Westinghouse)

Oxygen and Carbon in Silicon

James Corbett (Suny-Albany)

Solar Cell and I.C. Aspects of Ingot-to-Slice Mechanical Processing

Lawrence Dyer (Texas Instruments)

Defects and Device Performance

George Storti

The Device Engineer's Wish List to the Materials Engineer

1. SILICON OF LONG MINORITY CARRIER LIFETIME
   (e.g., 0.2 Ω cm p-type with τ > 500 μs)

2. SILICON OF REPEATEDLY UNIFORM LIFETIME
   (not 50-1000 μs)

3. SILICON WHOSE LIFETIME DOES NOT DECREASE DURING NORMAL DEVICE PROCESSING
   (a repeatable, uniform increase is o.k.)

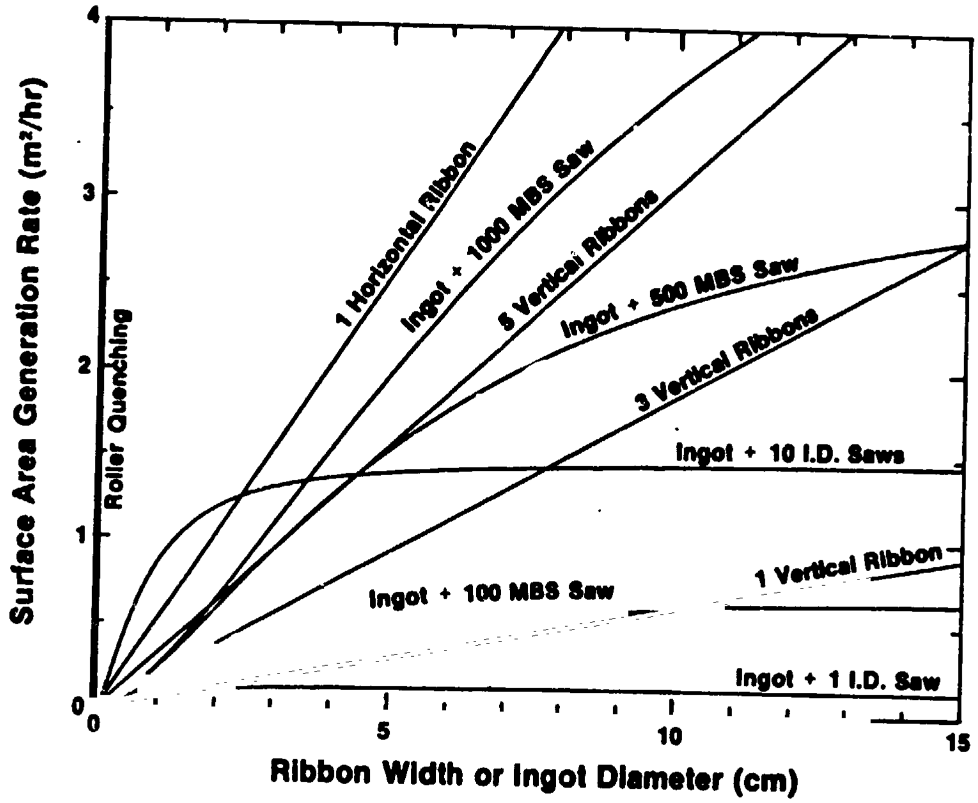
4. SILICON SHEET (WAFER) WHICH IS FLAT, AND STAYS FLAT THROUGHOUT NORMAL DEVICE PROCESSING

5. SILICON WHICH UNIFORMLY HAS REASONABLE MECHANICAL STRENGTH

6. SILICON SHEET OF LOW COST
   (<$50/m^2)

Efficiency/Yield-Limiting Materials Characteristics

- **Dislocations in grain boundaries**
- **Dislocations in subgrain boundaries**
- **Intragrain isolated dislocations**
- **Gross impurities: inclusions, precipitates**
- **Isolated impurities**
- **Dimensional evenness, processibility**



Criteria for the Ideal Sheet-Growth Method

- **Good Crystal Perfection**
- **Flat Smooth Surface**
- **High Purity**
- **Easy Control**
- **High Throughput**

FZ Single Crystal, 100 mm in Diameter
1.5 m in Length

Cz Single Crystal, 250 mm in Diameter
45 kg in Weight

Growth Conditions in 5-in. FZ and Cz Methods

	FZ* (1st + 2nd)	CZ
DIAMETER (mm)	128	130**
DIRECTION	<100>	<100>
POLY DIA LENGTH (mm)	128 1800	——
POLY WEIGHT (kg)	50	30***
GROWTH RATE (mm/min)	1st 4 2nd 3	1

* 2pass FZ shows higher single crystal yield than that of single pass FZ.

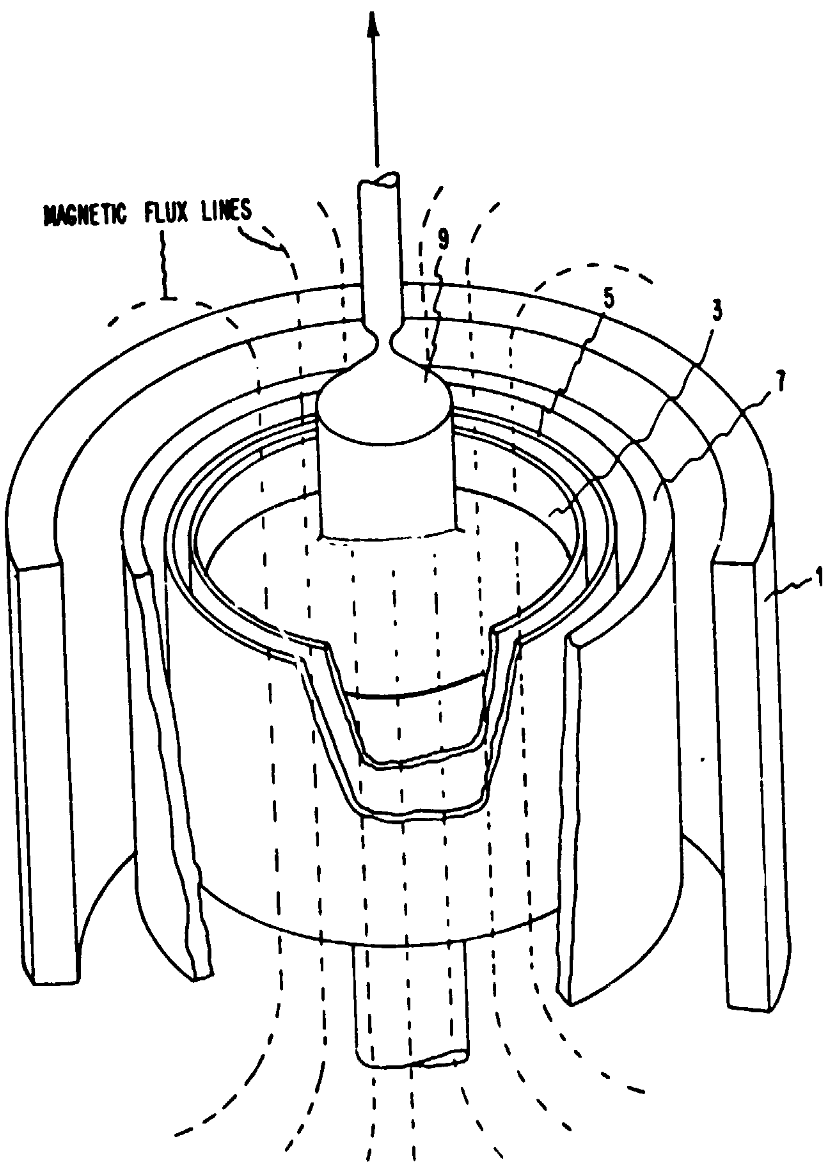
** FZ diameter control is easeir than that of CZ.

*** 30 kg charge in 5" shows the most effective productivity (productivity x yield).

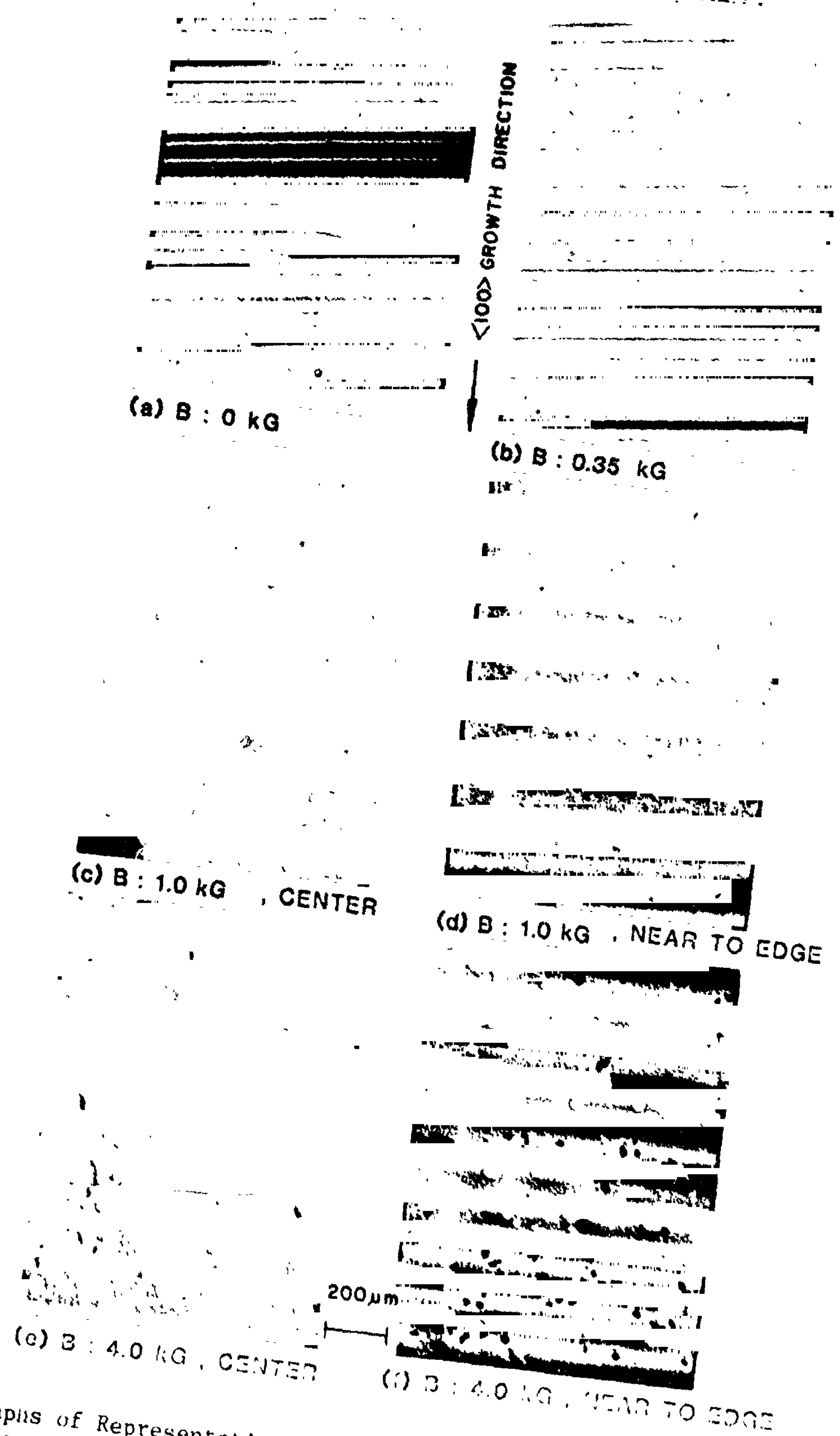
MCz Crystal Growth

APPARATUS FOR CZOCHRALSKI SILICON CRYSTAL GROWTH THROUGH AXIAL MAGNETIC FIELD FLUID FLOW DAMPING

K. M. Kim, G. H. Schwuttke and P. Smetana

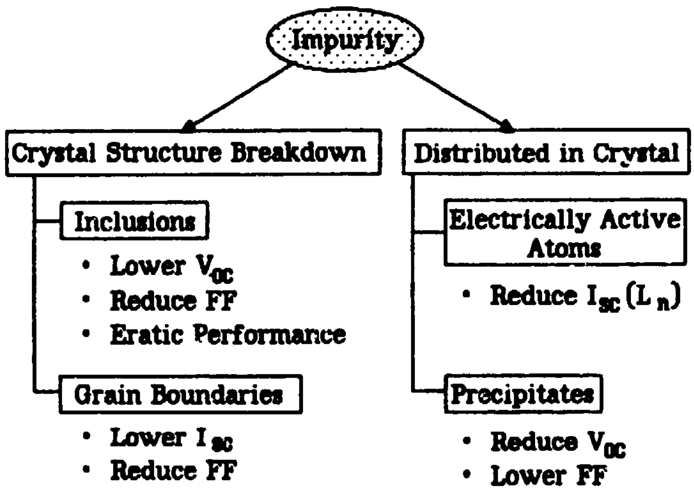


An arrangement is provided for utilizing axial magnetic fields to suppress the fluid flow in the melt of Czochralski-type silicon crystal growth systems.



Photomicrographs of Representative AMCz Crystal Sections. Note That Central Region of 4 kg crystal is free of striations; dislocation etch pits in (f)

Impurity Degradation Mechanisms in Silicon Solar Cells



Impurity Behavior

- **Degrade Junction**

  Cu, Ni

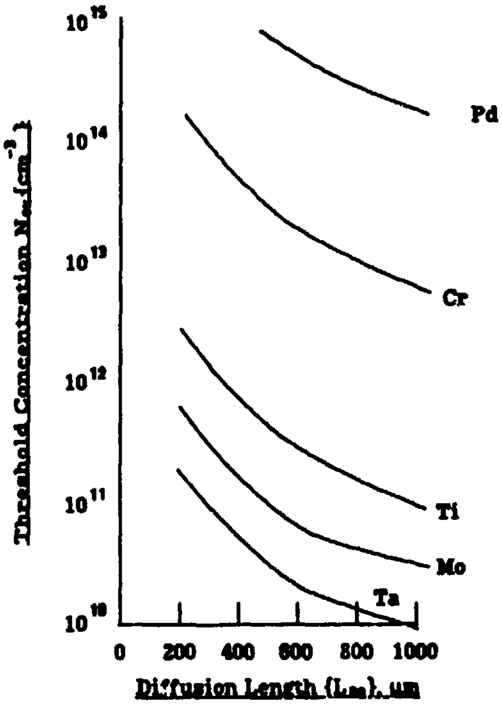
- **Reduce Diffusion Length**

  Nb, Ti, V, Ta, W, Mo, Pd, Au, Zr, Mn, Al, Sn

- **Both**

  Fe, Co, Ag

Variation in Degradation Threshold With Diffusion Length of Baseline SE Cell



Summary

1. Impurities Depreciate Cell Performance
   - Reduce Diffusion Length by Trap Formation
   - Degrade Junctions via Precipitates/Inclusions

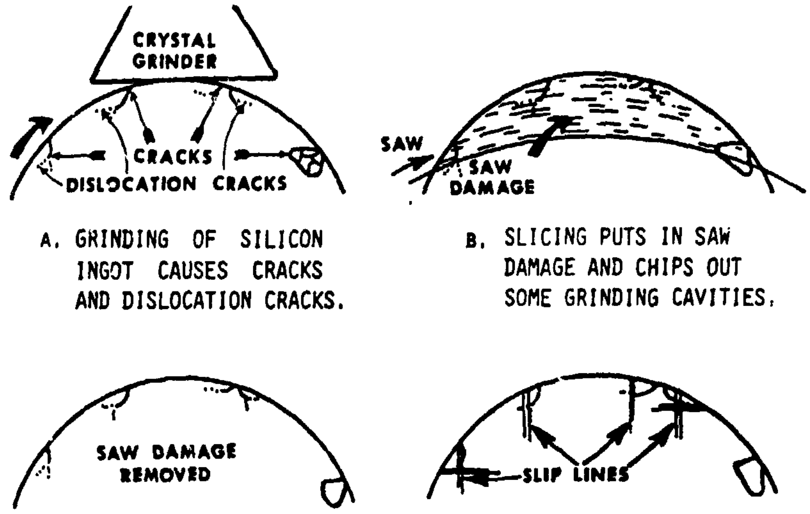
2. Impurity Model Describes Well the Behavior of Conventional Cells (SE)with Single and Multiple Contaminants

3. Models Can be Used to Understand Impurity Effects in:
   - High Efficiency Designs
   - Polycrystalline Material
   - Sheet or Ribbon Crystals

4. High Efficiency Devices More Sensitive to Impurities than Conventional Devices

5. Improved Data on Impurity Effects Required to Quantify Model Predictions for High Efficiency

Schematic of Slip Generation From Excessively Deep Crystal Grind Cracks



A. GRINDING OF SILICON INGOT CAUSES CRACKS AND DISLOCATION CRACKS.

B. SLICING PUTS IN SAW DAMAGE AND CHIPS OUT SOME GRINDING CAVITIES.

C. LAPPING, ETCHING AND POLISHING REMOVES SAW DAMAGE BUT NOT ALL OF THE GRINDING DAMAGE.

D. PROCESSING IN FURNACE OR EPI REACTOR GENERATES SLIPLINES.

Fig. 10. Crow's-foot fracture from burr on vacuum chuck.

Fig. 12. Edge crack from heat-treating silicon slice in quartz boat.

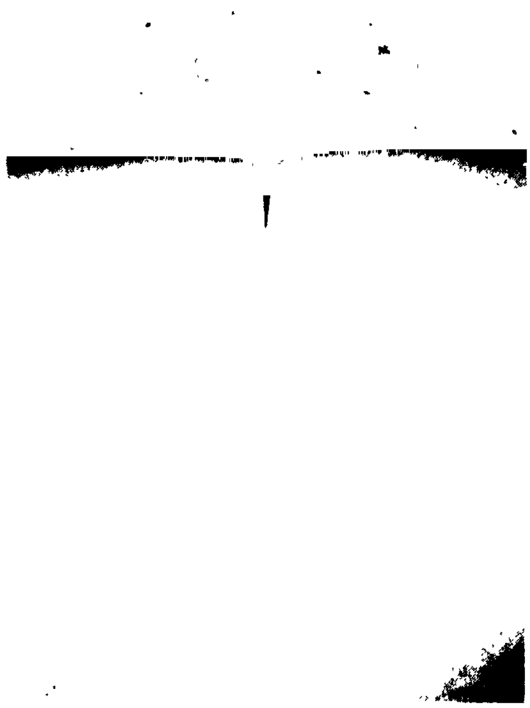


Fig. 13. Edge crack at polish.

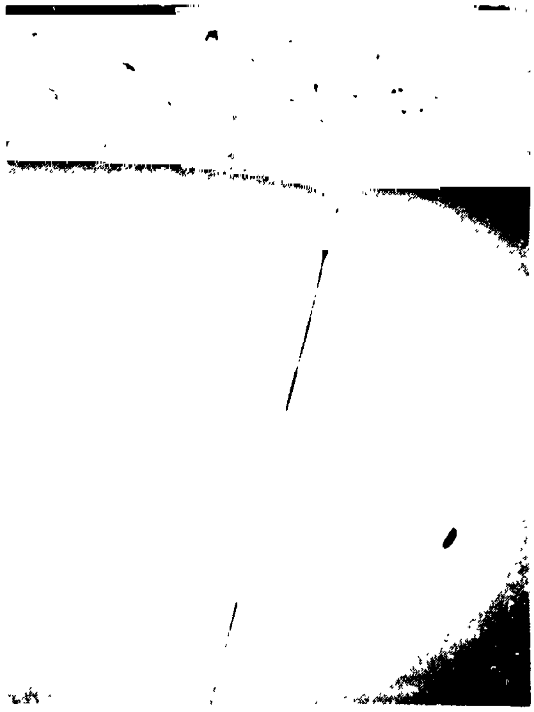


Fig. 14. Edge crack at polish.

Conclusions

1. Present-day FZ and Cz are of sufficient quality to obtain efficiencies in excess of 20%. FZ is the preferred material because higher diffusion lengths can be obtained for a given base doping

2. FZ and Cz silicon are very useful to the device researcher for determining the importance of the various loss mechanisms and for devising the processing technologies to reduce the losses

3. Economic cell-processing technologies that take advantage of the experience gained in the laboratory will also have to be devised

4. Ultimately, it is unlikely that either Cz or FZ silicon is economic for photovoltaics; this is true for any technology

5. The important issue for the alternate in silicon technologies is whether sufficiently high diffusion lengths for a given base doping and wafer thickness are achievable, and, if achievable, whether it can be done quickly and economically

6. Five-Year Plan does not include technology development effort on ingot growth and there are not sufficient funds to do all the research that needs to be done

Future Areas of Research

- **Technology development for float-zone-grown silicon is needed**
- **Implement innovative concepts to improve material perfection of Czochralski-grown silicon**
- **If ingot technology is supported, need for wafering research is unquestionable**
- **Continue research in ribbon technology to develop "ideal" ribbon growth process**