

A PULSED ELECTRON ACCELERATOR USING SOLID DIELECTRIC ENERGY STORAGE

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Abstract

A new accelerator, designated SPI-PULSE 7000, was designed to produce high-current (>50 kA) low-average-energy (10-30 keV) pulses of electrons with beam diameters up to 15 cm. The accelerator will be used to anneal ion implantation damage in silicon solar cell wafers in a single 100 ns pulse.

The 2.6 kJ energy store of the accelerator consists of an array of cylindrical solid dielectric transmission lines which are d.c. charged to voltages up to 300 kV. As many as 19 of the 3 nF lines can be discharged in parallel by a single spark switch. The lines are cast from high-dielectric-strength epoxy using techniques developed at Spire.

Introduction

An accelerator, designated SPI-PULSE 7000, has been designed to produce high-current (>50 kA), low-average-energy (10-30 keV), short-duration (100 ns) pulses of electrons with beam diameters up to 15 cm.

The accelerator will be used to anneal ion implantation damage in silicon solar cell wafers in a single-pulse-per-unit production line processing mode. The processing rate will be a maximum of one wafer every 2 seconds in continuous duty, and the accelerator must perform reliably with reproducible pulse characteristics.

To meet these goals, a d.c. energy store charging method was chosen which, through simplicity and careful control of the electrical stresses, has a continuing record of reliability. The energy store is a modular assembly of solid dielectric insulated, coaxial lines, directly charged and then discharged to the load via a two-electrode switch, triggered by a pneumatically operated, trigger electrode — a mechanical version of the trigatron. This triggering mode is compatible with the arrival speed of the transported wafer. An important virtue of this method is that there is no prepulse at the diode load during the charging cycle, which contributes to beam quality and reproducibility.

The beam philosophy for this accelerator, which concentrates upon using suitable and acceptable techniques for industrial usage, also coincides with some general repetitive pulsed power design trends which seek to transfer a single-pulse technology to the more rigorous requirements of repetitively pulsed systems.

It has been recognized that reliability in repetitive pulsing is best achieved by arranging for the simplest power-conditioning chain between prime power and the final energy store.¹ A solid dielectric, insulated store provides for this, since it can be charged over a large proportion of the interpulse period. This use of a solid dielectric store is a departure from single-pulse technology, which is directed towards high energy density storage in liquid insulated PFL's, particularly water, by submicrosecond charging periods. This change to simpler power-conditioning systems is exemplified by the development of the compensated alternator (compulsator), which will have the potential to charge solid or specially treated liquid insulated PFL's to $10^5 - 10^6$ volts in 50-100 microseconds.

The parameters and configuration of the SPI-PULSE 7000 accelerator will be described, and some emphasis will be given to the solid line design and construction.

Electron Beam Requirements

For electron beam annealing of ion implants, the pulsed beam must melt the material surface within a depth range of $0.5-5.0 \mu\text{m}$. The energy delivery time must be short compared with heat diffusion times, $0.1 \mu\text{sec}$ or less in this case. To deposit this energy in a shallow layer and without electron radiation damage, the average electron energy must be in the range of 10-20 keV. Figure 1 shows a calculation of melt depth in crystalline and amorphous silicon as a function of electron beam fluence; the fluence required is a minimum of 1 J/cm^2 .

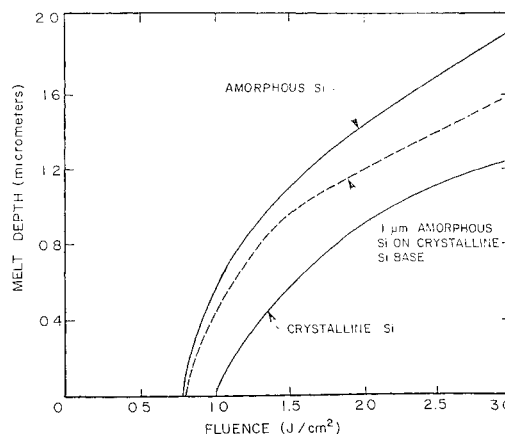


Figure 1. Computer calculation of melt depth in crystalline and amorphous silicon as a function of pulsed electron beam fluence.

On resolidification the surface exhibits dislocation-free regrowth for single crystal materials such as silicon.

The silicon area to be processed is approximately 80 cm^2 . After an evaluation of the various methods of applying the electron beam — by scanning, overlapping pulses or single pulse — it was decided to process by the single pulse to ensure uniformity and consistency of the product.

By adopting this route to processing a 10 cm diameter silicon wafer, the beam current required for an adequate fluence of 10-20 keV electrons was 50 kA. This resulted in a diode impedance requirement of 1.0 ohm at peak pulse and a diode with propagation-limiting self-magnetic and electrostatic fields. The diode was designed with a 15 cm, field emission cathode with an adjustable anode-cathode gap. The spacing between the mesh anode and beam target was also designed to be adjustable. Beam control was optimized by the provision of an axial magnetic field of 1-2 kilogauss. With this applied field the electrons incident on the silicon are not normal to the surface, and therefore surface heating is more efficient, which allows the use of higher energy electrons than for normal incidence.

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Pulse Generator Requirements

The optimum parameters for the diode and pulse generator to give the required fluence ranges were obtained from a simple model of a capacitor discharging to a load, conforming with Child's law, via a circuit inductance. With reasonable values determined for cathode-anode dimensions and charge voltage, the pulse generator capacitance and inductance were optimized for the best overall performance. Figure 2 shows this process for a set of diode and charging parameters. Figure 3 shows the diode pulse characteristics for the same parameters and circuit values of 40 nF and 100 nH.

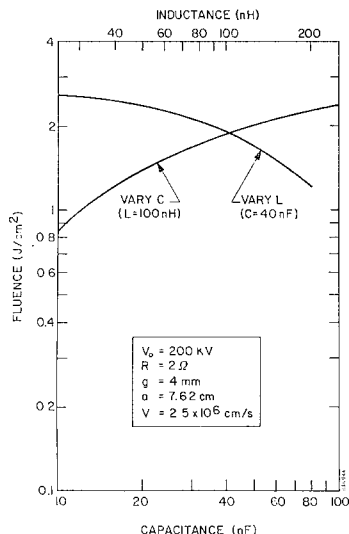


Figure 2. Variation of fluence on sample with changes in pulse generator parameters. (C=capacitance, L=inductance, V_0 =charging voltage, R=single line impedance, g=diode A-K gap, a=cathode radius, V=velocity of cathode plasma. Same parameter used to compute data in Figure 3.)

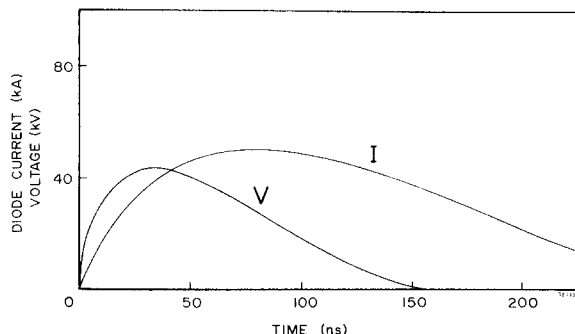


Figure 3. Diode pulse characteristics for electron beam annealer.

The pulse generator design goal was to charge the 40 nF capacitance to 200 kV or greater and to obtain a capacitor-switch-load geometry which would provide the discharge characteristics of Figure 3. To ensure a safety margin for fluence, the charging supply and capacitor rating were to be adequate for 300 kV operation.

The choice of the capacitive energy store type is one of the major features of this accelerator. Of the possible dielectric systems which can be considered for a slowly charged, rapidly discharged energy store, the solid dielectric insulated transmission line has many virtues:

- High energy density
- Simple structure without auxiliary equipment
- Low losses
- Consistent, fast discharge characteristics

For long life and reliability it is necessary to control the electric field and practice quality control. Working within these constraints Spire has had excellent experience with these stores² and has chosen to configure the SPI-PULSE 7000 store with 19 solid-dielectric coaxial line modules, each module being 3 nF with an impedance of 2 ohms.

Solid Dielectric Insulated Lines

As mentioned, there is interest in the development and application of solid dielectric energy stores to promote reliability through simpler power conditioning chains. D. Brower et al.³ develop arguments for this trend and note that a modest stress of 1 MV/cm in a solid dielectric would yield an energy density about three times that obtained in a water-insulated line stressed reasonably at 0.1 MV/cm.

In the initial evaluations of various solid dielectrics for transmission line applications, Spire confirmed the high intrinsic strengths that could be obtained. Figure 4 illustrates the test configuration used for cast samples, and Table 1 gives some of the experimental results for d.c. stressing. When applying solid dielectrics to line energy stores, the important issue is to exploit these high intrinsic strengths in a controlled and reproducible way.

Depending upon the application, there are different factors which influence the choice of configuration for a solid dielectric line. Strip-line geometry, in single-line or Blumlein form, is sometimes preferred because of assumed simple construction and flexibility. In these cases the maximum electrical stresses are those supportable at the strip edges and are significantly less than the intrinsic strength level.

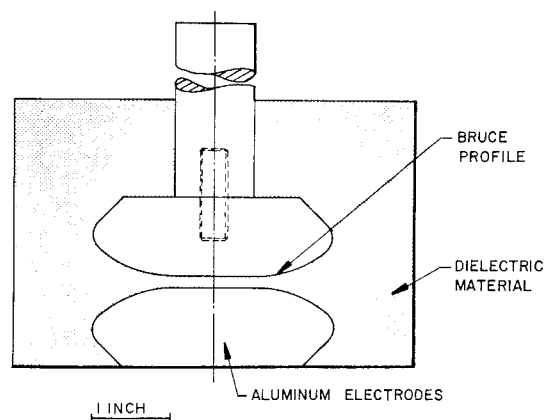


Figure 4. Small-sample test configuration for cast dielectrics.

Table 1. Dielectric strengths of materials considered for d.c. charged Lines.

Material	Expected Value (MV/cm)	Measured Value (MV/cm)
Lucite (Polymethyl- methacrylate)	3.3	2.8
Mylar (Polyethylene terephthalate)	3.6	3.4
Polyurethane		
USC ⁽¹⁾	3.0	1.1
UEP ⁽²⁾	—	>3.0
Epoxy		
DS ⁽³⁾ 5009	—	1.4
E&C ⁽⁴⁾ Stycast 2850	3.2	1.8
E&C Stycast 1264	2.9	>3.0

Notes:

- (1) Urethane Systems, Inc., Stockton, California
- (2) Urethane Engineering Products, Inc., Johnston, Rhode Island
- (3) Dielectric Sciences, Inc., Woburn, Massachusetts
- (4) Emerson and Cuming, Inc., Canton, Massachusetts

For coaxial geometry these enhancements are avoided; although the energy density is not uniform within the dielectric due to the inverse dependence of the field upon radius, this geometry is potentially superior to the strip line. D. Brower et al. note that, ignoring area effects, the two forms of line have equivalent average energy densities over the total volume, provided that the field enhancement of the strip-line edge is not greater than 1.6.

The coaxial geometry was chosen for the SPI-PULSE 7000 accelerator because the electric fields could be carefully controlled and the manufacturing techniques ensured reproducible quality. Each line has a capacitance of 3 nF and inductance of 14 nH; the outer diameter is 24 cm with a dielectric thickness of 0.8 cm. The line is fabricated by casting high-strength epoxy around a machined and polished inner electrode. The outer electrode is formed by a zinc spray coating upon the epoxy. Figure 5 shows the manufacturing stages for the line.

Up to 19 of these line modules can be mounted vertically upon a common, circular plate electrode, as shown in Figure 6. This plate also carries the upper discharge switch electrode. The assembly is mounted in a pressure vessel and a pressurized environment of SF₆ is provided for the capacitor terminations, switch and high voltage support structure. A view of the overall accelerator system is shown in Figure 7.

Conclusion

The accelerator has been assembled and tested with eight of the capacitor modules charged to 180 kV in a 100 psi N₂/CO₂ environment. For these conditions the fluence

is sufficient to anneal 80 percent of the 10 cm diameter target wafer. Axial and radial beam uniformity has been satisfactory with an axial magnetic field of ~1 kG. Values less than this give high fluence on axis; greater values (~2 kG) give an annular beam. The next development phase will increase the capacitor modules to twelve.

With different diode configurations, this accelerator can be used for different purposes: x-ray generation for SGEMP testing, IEMP simulation, laser pumping, etc. The solid dielectric line technology permits a wide range of charging methods, and therefore with appropriate switch selections the pulse repetition rate may be raised significantly. The coaxial lines may be readily cooled for the higher duty cycles.

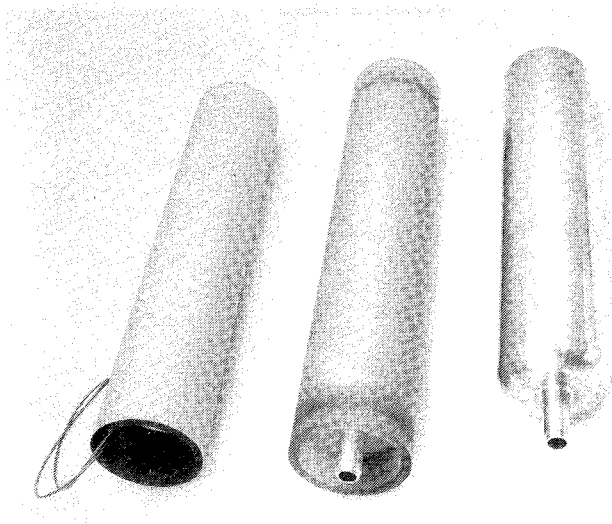


Figure 5. SPI-PULSE 7000 energy storage capacitor-manufacturing sequence.

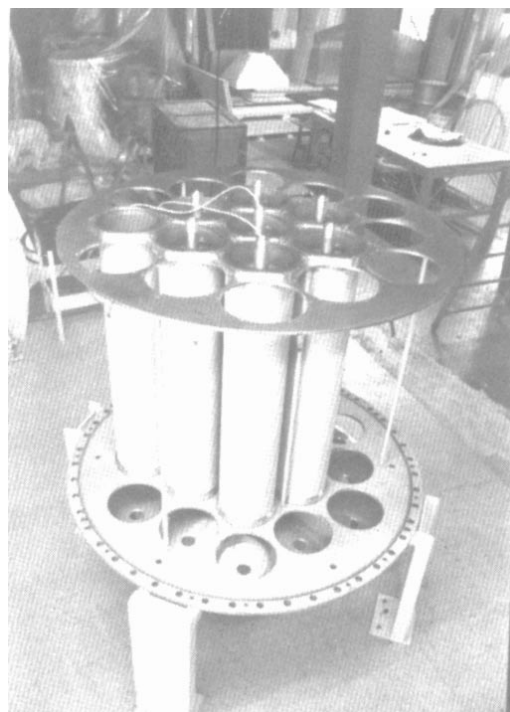


Figure 6. Nested set of dielectric storage line modules.

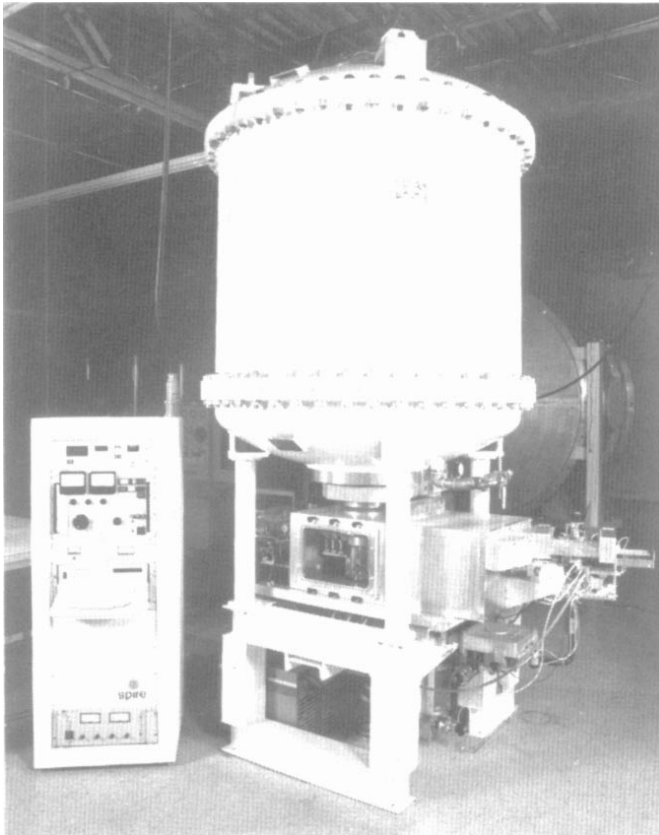


Figure 7. SPI-PULSE 7000 Accelerator.

Recognition

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3. D. F. Brower et al., "Study and Development of Key Elements of a High Repetition Rate, High Energy Pulse System", University of Texas, Austin, Texas, Doc. FRCR No. 201, Final Report DASC-60-78-C-0085, August 1979.