

THYRATRON MODULATORS IN PLASMA SOURCE ION IMPLANTATION

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Abstract

Plasma Source Ion Implantation (PSII) is an emerging technology which can be used to harden metal surfaces in a conformal manner. North Star Research Corp. (NSRC) is building a unique implanter system for Empire Hard Chrome which will be the first truly commercial implanter of this type. The choice of pulsed power technology for this application is important from the standpoint of both reliability and compatibility with the basic plasma processes under consideration. In this paper, we will evaluate the various possible pulsed power system choices including thyatron modulators, hard tube modulators, and crossatron modulators in the context of compatibility with the plasma and implantation process. Currents in the hundreds of amperes at 80 - 100 kV are clearly found to be desirable based on the requirements of the process. This leads to the logical choice of thyatron/transformer modulators at lower average powers, or Crossatron modulators at higher average powers. We also discuss PFN design for thyatron modulators for the universal PSII-type waveform. A thyatron modulator was selected for the Empire implanter due to the requirements for low cost and high peak current.

1.0 Introduction and Basics of PSII

Ion implantation has the potential to improve the wear and corrosion properties of a wide variety of components, and it is in common use reducing corrosion and wear in parts such as artificial hip joints¹. This technology has more significant applications in the area of wear reduction in metal and plastic forming tooling. There have been a number of extensive reviews of ion implantation effects in the literature^{2,3,4}. Reductions in the rate of wear of up to a factor of 40 in EN40B steel have been observed, probably due to the presence of interstitial nitrogen in the lattice. Ion implantation differs from most other surface modification processes in that it is intrinsically a non-equilibrium process, and is therefore not limited by the physics of equilibrium processes. Both non-equilibrium states and amorphous states can be produced through implantation. A number of organizations have significant programs in ion implantation.⁵

Conventional implanters produce a unidirectional beam which strikes the whole surface at normal incidence only for flat surfaces. In positions where the beam is at an angle (say at an angle θ) to the surface, the depth of implantation varies as $\cos\theta$, and the flux varies as $1/\cos\theta$. The process of surface thinning due to sputtering also has a rate which varies as $1/\cos\theta$. Since

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the sputtering process removes surface material, sputtering imposes a limit on the total number of implanted particles by reaching a state where as many particles of the implanted specie are removed by sputtering as are implanted. For example, if the sputter yield is Y , the equilibrium dose fraction is $1/Y$. Therefore if $Y = 3$, the equilibrium dose fraction is 33 %, but if $Y = 3$ and $\theta = 60$ then the equilibrium dose fraction is 17 %.

If a shape being implanted is more complex than a simple flat surface, these dependencies reduce the depth of the implant for non-normal beams, and decrease the fraction of the implant which is retained in the surface. Implantation of a complete object also involves rotation of the product and programming of that rotation pattern for each object treated. In practice, features such as curved surfaces and indentations are difficult to treat by conventional ion implantation (see Figure 1).

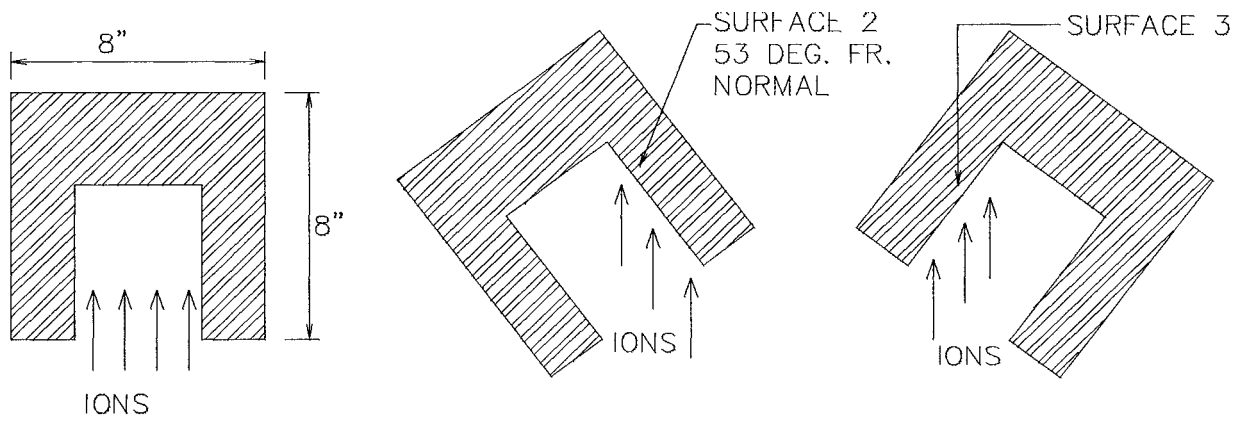


Figure 1 The method for implanting an indentation using a conventional implanter.

From Figure 1, it is clear that the indentation (surfaces 2 and 3) can best be treated with conventional ion implantation at an angle of 53 degrees. At that angle, the maximum implant depth is decreased by 40 %. Perhaps more serious than the reduction in depth is the reduction in sputter limited dose. The sputter limited retained dose for nitrogen ions in steel is about 25 % of solid density for normal incidence ions. This drops by 40 % due to the increase in sputtering coefficient with angle away from normal.

Plasma Source Ion Implantation (PSII) overcomes some of the problems of conventional implantation by immersing the object being implanted in a plasma which can conform to the surface. The object is then (negatively) pulse biased. This type of ion implantation has been performed successfully by Conrad⁶ with a variety of gaseous species and by Adler⁷ using a thyatron/transformer/pulse forming network system and a vacuum arc ion source.

A difficulty with many existing PSII systems is that the "sheath" (which is the boundary layer between the implanted object and the plasma) is very thick - typically 10 - 30 cm. As such, smaller features of the object and indentations as shown in Figure 1 are not significantly implanted. The indentation sides (surface 2 and surface 3) of Figure 1 will be implanted only in the very early phases of the implant, and those phases of the implant occur at low energy due to capacitive effects in existing ion implantation systems.

For Nitrogen ions, we can find the sheath distance as a function of current I (amperes), voltage V(MV), Secondary electron coefficient S and implant area (cm²). The formula is simply derived from the Child - Langmuir law, and it is:

$$d = 3.5(1+S)A^{1/2}V^{3/4}/I^{1/2}$$

where we assume that the ion source produces a plasma with equal parts of N⁺ and N⁺² and an average mass of 21. If we set d = 5 cm, V = .06 MV, and A = 6000 cm² (a 1 ft. cube) and we recall that S is approximately 7 then we require I = 340 amperes. Larger areas clearly require much higher currents.

The time dependence of the PSII pulse can be derived in general from first principles as shown by Scheuer⁸. Without going into detail, the basic dependence which results from the interplay of Child-Langmuir ion emission from the edge of the sheath, and sheath erosion is that the current I varies as time to the -2/3 power. We therefore find that a modulator for PSII must produce high currents near the beginning of the pulse, and much lower currents later on. Fast risetimes are important because low energy ions (<30 kV), due to their thin penetration, are likely to be lost from the surface due to sputtering. Ions accelerated to low energies during the risetime tend to thin the implanted layer due to sputtering of the surface of the part being implanted. The basic time dependence results in pulses in which most of the current is delivered in the first 10 microseconds.

2.0 PSII Pulsed Power Technologies

A number of technologies exist for performing PSII. For example, Los Alamos National Laboratory has a 20 kW average power PSII setup driven by a high voltage power supply and a 25 A switching tube. This approach (using a so-called "hard tube" switch) can be used for currents of up to about 120 amperes peak. In general, because of the current limitations of existing tubes, it cannot be used for conformal PSII with smaller feature sizes.

The Hughes Crossatron switch is an effective switch at voltages up to 95 kV which is capable of overcoming the current limitations of conventional hard tubes. The potential drawback of the Crossatron is that in the case of an arc between the implanted part and the wall, the current grows rapidly, and the Crossatron may be difficult to turn off. The relatively high voltage of the Crossatron based power system and the requirement that oil be used are also drawbacks.

Line type Modulators in which a thyatron switches an inductive-capacitive "Pulse Forming Network" (PFN), (possibly with a pulse transformer in order to step up the voltage) are an alternative to hard tube systems. The virtues of these systems are that the pulse forming occurs at relatively low voltage (35 kV) so that the PFN can be in air, the thyatrons are inexpensive and reliable, and the current delivered into a fault can be limited as long as the reverse PFN voltage is "clipped". NSRC delivered an 8 kW, 80 - 120 kV implanter to Eaton Corp. in 1993 which demonstrated that thyatron/PFN based PSII is effective for this type of implantation.

A thyatron PFN with a 35 kV charge voltage delivering 80 kV to the target with 1000 amperes peak requires only 5000 amperes thyatron current. The energy per pulse in such a system with a 3 microsecond pulse duration is typically 80 J, so a 40 kW system would operate at only 500 Hz. These parameters are in the center of the range of thyatron parameters. In such a system, the primary limitation will be the plasma produced, and we believe that plasma production at the required levels (5×10^{10} - 2×10^{11}) has been demonstrated (Jay Scheuer & Michel Tuszewski, LANL, private communication). In the next section, we outline the design of a thyatron/pulse transformer system which is designed in the parameter range between conventional PSII, and conformal PSII.

3.0 Empire Implanter

The Empire Implanter consists of the following system:

- Main Vacuum Chamber
- Manual Vacuum System w/Automatic Gate Valve
- Automatic Gas Pressure Controller
- Power Feedthroughs
- Thyatron/PFN/Pulse Transformer Pulsed Power System
- Cooling Feedthroughs
- Cooling coils wrapped around the chamber for a total of 3.5 Gallons/minute at 40 lbs drop.
- Low Frequency RF Plasma Power System
- Nominal 1 m long X 1 m diameter chamber

The Standard Operating Modes to be provided in the ion implanter will be:

- 100 kV/280 mA average (total current at a voltage above 40 kV)
- 75 kV/350 mA average (total current at a voltage above 40 kV)
- 60 kV/420 mA average (total current at a voltage above 40 kV)

at up to 400 pulses per second and 100 J/pulse energy stored.

The system will use an SCR/transformer pulse charge in order to provide a system immune to thyatron "latchup".

3.1 Circuit Simulations

We simulated various PFNs with the objective of producing a waveform which has the predicted PSII current pulse shape, yet has a "flattop" voltage pulse. We found that such PFNs exist as shown in Figure 2. The assumed energy stored in the 6 ea. X 0.38 microfarad capacitance is about 110 Joules at 31 kV. The current loading goes from approximately 300 amperes at its peak, to about 75 amperes at the effective end of the pulse. The purpose of the simulations was to develop a waveform which had a flat top while driving a very non-linear load. Once that was designed, our goal was to design the various clipper circuits. The capacitor value was selected based on our capacitor purchase for the project.

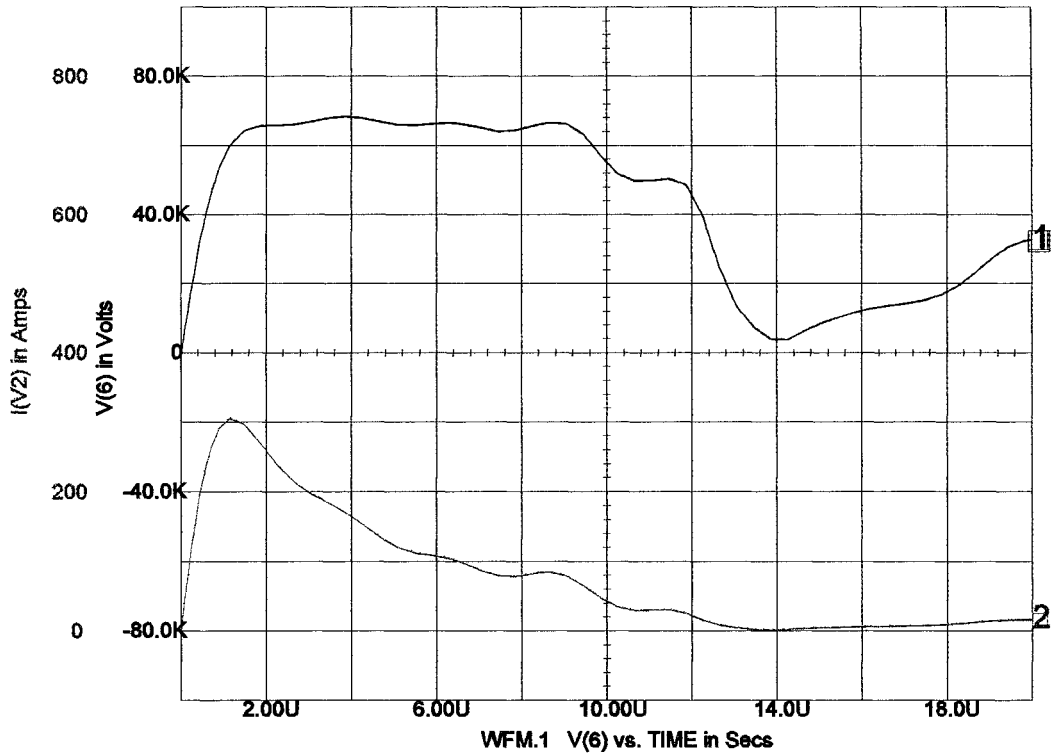


Figure 2 Simulated Thyatron modulator waveforms with tapered PFN.

The clipper circuits were straightforward to design and lead to capacitor reversals of less than 15 % for all capacitors. At that level, we expect a capacitor life of approximately 10^{10} - 10^{11} pulses.

3.2 Pulse Transformer

The design of the pulse transformer will be more conservative than that used for the Eaton transformer. Although that transformer has no failures and is conservatively designed, we have no test data from it. The design rule to be used is a pulsed value of 45 kV/cm. in an oil/polypropylene aggregate at 100 kV. The transformer has been designed using the TRPULSE code at NSRC. It is expected to give a pulse with a submicrosecond risetime. The specific design values from the spreadsheet and core purchase order are:

Minor Cross-section	2" X 2"
Total Height	15"
Total Core Width	8"
Secondary - Ground Minimum Spacing	1"
Turns for 100 kV	32:180

Turns for 65 kV	32:108
Primary Inductance with secondary open	5000 μ H
Predicted Core Dissipation (400 Hz.)	1.2 kW
Flux Swing	+/-1 Tesla
Core Material	2 mil silicon iron
Core Surface Area	324 in ²
Core Operating Temperature	65 C

The design of the transformer will have a linear winding on the primary with the usual tapered secondary.

4.0 Conclusions

The conclusions of our work are that a thyatron modulator with a fast transformer and a tailored PFN can produce waveforms which are attractive for Plasma implantation. A thyatron driven system will be most attractive if more conformal implantation is required.

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