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Title: A Commercial Plasma Source Ion Implantation Facility

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A COMMERCIAL PLASMA SOURCE ION IMPLANTATION FACILITY

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Empire Hard Chrome has recently installed commercial plasma source ion implantation (PSII) equipment built by North Star Research Corporation. Los Alamos National Laboratory has assisted in this commercialization effort via two Cooperative Research and Development Agreements to develop the plasma source for the equipment and to identify low-risk commercial PSII applications. The PSII system consists of a 1m x 1m cylindrical vacuum chamber with a pulsed, inductively coupled rf plasma source. The pulse modulator is capable of delivering pulses with peak voltages of 100 kV and peak currents of 300 A at maximum repetition rate of 400 Hz. The pulse modulator uses a thyratron tube to switch a pulse forming network which is tailored to match the dynamic PSII load. In this paper we discuss the PSII system, process facility, and early commercial applications to production tooling.

1. Introduction

Plasma source ion implantation (PSII) was first introduced in the mid 1980's [1] with PSII related research now being performed at over 30 institutions worldwide. For certain applications PSII has matured to the point of commercialization. Via a Cooperative Research and Development Agreement (CRADA), a partnership between Los Alamos National Laboratory (LANL) and Empire Hard Chrome of Chicago, IL has been established to commercialize PSII. The site of the worlds largest PSII facility, LANL has pursued scale-up through collaborations with several industrial partners over the last five years. Through industrial field testing, Empire Hard Chrome (EHC) has demonstrated the ability of nitrogen implantation to greatly increase the lifetime of chrome plated components using conventional line of sight ion implantation. Empire was also encouraged to pursue PSII by results showing dramatic hardness and wear increases of chrome electroplating via PSII [2,3]. Based upon these successes, EHC has contracted with North Star Research Corporation of Albuquerque, NM to provide a complete PSII system. Through the CRADA agreement, LANL has provided the plasma and materials expertise required by EHC to develop implantation recipes, optimize process conditions, and qualify high probability applications to help make this venture a success.

LANL has also entered into a CRADA with North Star Research Corporation to develop the pulsed rf, inductively coupled plasma source for the system to be used by Empire Hard Chrome. Results of the LANL/North Star project are described in another paper [4]. In this paper we discuss the PSII facility constructed by Empire Hard Chrome, the North Star Research implanter and the early commercial applications of PSII at Empire.

2. PSII Facility

The PSII facility constructed by Empire Hard Chrome covers 100 square meters. The facility has an overall electrical power capacity of 400 A at 480 V. A water cooling system has been constructed to cool the vacuum pumps, vacuum chamber walls and the processed parts. The cooling system consists of a 40 kW water chiller, a 2500 l chilled water reservoir and three circulation pumps.

The accelerated secondary electrons produced through PSII necessitate some x-ray shielding. The shielding constructed by Empire consists of 6 mm lead sheet covering the vacuum chamber combined with a 15 square meter, 0.38 m thick concrete block enclosure with a 6 mm lead sheet sliding door. This conservatively designed system reduces the x-ray exposure to less than half of the natural background level when running at full system power.

3. PSII System

The PSII system constructed by North Star Research Corporation shown in Fig. 1 consists of a vacuum system, pulsed plasma generator, and a high voltage pulse modulator. These subsystems will each be described in detail below. The design philosophy for this system was to advance the state of the art of PSII hardware while maintaining reliability and affordability.

For PSII to be commercially viable, implantation must be performed conformally and over large areas. These two process requirements place constraints on system design. A difficulty with many existing PSII systems is that the sheath (the boundary layer between the implanted object and the plasma from which the implanted ions are extracted) is very thick - typically 15 - 30 cm. As such, smaller features and indentations of the object are not uniformly implanted.

The peak current which must be delivered by the pulse modulator for a conformal, large area implant can be estimated using the Child-Langmuir law:

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

where we assume that the plasma source generates a plasma with equal parts of N^+ and N^{2+} and an average mass of 21. If we set the sheath thickness d = 5 cm, the voltage V = 0.06 MV, the target area A = 6000 cm^2 (1 ft. cube) and assume that the electron emission coefficient $\gamma = 7$ then we require a current I = 340 A. Larger areas will require even higher currents to retain conformality.

The high densities required for conformal implantation (on the order of $1x10^{10}$ cm^{-2}) must be generated by the plasma source at a pressure low enough to limit charge exchange collisions as the ions cross the accelerating sheath. Applying pulsed high voltage to the target in a high plasma density draws a high peak current which must be supplied by the pulse modulator. Also, implantation over large areas requires large peak current. Conformal implantation over large areas therefore requires an efficient high density plasma source and a pulse modulator capable of delivering high peak currents.

The vacuum chamber is a 1 m long, 1 m diameter, 13 mm thick aluminum cylinder with a sliding door. The chamber is cooled by 15 °C water circulating at 40 liters per minute through 10 mm aluminum tubing welded to the outside wall. A Leybold D-30A rotary vane pump and a Varian VHS-6 oil diffusion pump evacuate the system to a base pressure of $1.0x10^{-5}$ mbar. The vacuum pressure is measured by thermocouple and Penning gauges. The high voltage is connected to the processed part via an epoxy feedthrough with a water cooled cap. This feedthrough also provides water cooling to the processed part to prevent overheating.

A pulsed rf source is used to generate the plasma. The burst of rf is timed such that the plasma generation coincides with the high voltage pulse applied to the target. An example of the typical timing sequence is shown in Fig. 2. The pulsed rf is coupled inductively to the background gas via an immersed "stove top" coil. Approximately 10 pulses at 330 kHz are applied to the antenna resulting in a plasma density on the order of $1x10^{10}$ cm^{-2}. An advantage of this source is the high plasma density generated at low average power and low fill pressures. Also, the high instantaneous power applied during the burst produces a large amount of atomic nitrogen ions. The atomic ions (N^+) have a deeper penetration and higher retained dose than molecular ions (N_2^+).

A hot filament is also employed enabling operation of the rf source at reduced (<1.5 mbar) pressure. More details of the source and generated plasma are available in reference [4].

The pulse modulator is based on a pulse forming network switched by a thyratron tube. The thyratron allows delivery of high peak current at low cost with high reliability [5]. The modulator is designed to deliver 100 J pulses at up to 400 Hz repetition rate for a total power of 40 kW. The pulses can be applied with 100 kV peak voltage and 300 A peak currents.

The pulse forming network (PFN) is tailored to efficiently couple power to the dynamic PSII load impedance. The optimum PFN configuration was designed using computer simulation to keep a flat top voltage with a current loading from 300 A at the peak to about 75 A at the end of the pulse. Clipper circuits were added at each stage of the PFN to keep voltage reversals of less than 15% for all capacitors. At this level, we expect a capacitor life of 10^{10}-10^{11} pulses.

One drawback of the pulse forming network is the need to keep the plasma load impedance within a certain range for optimum performance. If the plasma impedance is lower than the design point (lower density or smaller surface area), ringing in the pulse forming network generates secondary pulses at lower voltages which can cause sputtering and reduced retained doses. However, this limitation is mitigated to a great extent by the fast (~1 μsec) risetime produced by the modulator.

A more quantitative comparison can be drawn between the performance of thyratron and vacuum tube based modulators by looking at the inferred energy spectrum of the ions collected by the target. The energy spectrum can be inferred from the measured waveforms for applied voltage and target current. Since the target current is the sum of the ion current collected and the emitted secondary electron current, the current waveform must be divided by the proper voltage dependent electron emission coefficient. For this comparison, the electron emission coefficient was assumed to vary with the square root of the voltage.

Fig. 2 compares the inferred energy spectra of collected ions for the North Star Research thyratron switched PFN and the vacuum to be switched capacitor bank used by Los Alamos National Laboratory [6]. The NSRC spectrum was obtained for a worst case waveform in which a low voltage (<10 kV) secondary pulse followed the main voltage pulse due to an impedance mismatch between the target load and the PFN. The NSRC waveform had a 1 μs voltage risetime. Both implants were performed on targets of roughly 0.5 m^2. The LANL spectrum was obtained for an implant with a 5 μs voltage risetime. Both spectra show the low energy tail inherent in PSII. While the LANL energy spectrum has a higher peak energy (the North Star implantation voltage was reduced due to arcing of the target), both spectra show a vast majority of ions striking the target at 40 keV and above. Ions striking the target with energies greater than 40 keV contribute the most to the quality of the implant due to their deeper penetration and higher retained dose.

4. Initial Commercial Applications

One of the first commercial applications pursued by Empire Hard Chrome has been the treatment of rolls used to form aluminum rod. The rolls are used by the Aluminum Company of America in its Massena, NY production facility. Two pairs of H13 rolls from two stages of the twelve stage rod forming process equipment were chosen for treatment. The stage II rolls are 400 mm in diameter, 150 mm wide and weigh approximately 75 kg.

The wear treatment consisted of 13 μm of electroplated chromium followed by nitrogen implantation. The implantation was performed in nitrogen gas with a peak voltage of 60 kV and an average current collected during the pulse of 80 A. Using a numerical model of sheath propagation and current collection [7] it is estimated that the plasma density was approximately 1×10^{10} cm^{-3} yielding a 14 cm final sheath thickness.

The treated stage II rolls were tested under actual manufacturing conditions. Ion implantation following chrome plating increased the useful life of the rolls by a factor of two over chrome plating alone, thereby lowering overall process costs by reducing production downtime.

5. Conclusions

Following a decade of research and development PSII is now available commercially for mature applications. Through collaborations with Los Alamos National Laboratory, Empire Hard Chrome and North Star Research Corporation have assembled a commercial PSII facility and have begun treatment of industrial parts. The PSII system constructed by North Star has a high current pulse modulator and high density plasma source which enable conformal implantation over large areas. It is hoped that this system will provide high quality implants at a lower price than other implantation systems to enhance the industrial acceptance of ion implantation for a wide variety of commercial customers.

Acknowledgments

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Figure captions

1. Photograph of the North Star Research Corporation Plasma Ion Implanter installed at Empire Hard Chrome, Chicago, IL.

2. Schematic of the timing sequence of the North Star Research Corporation Plasma Ion Implanter showing (a) modulator charge pulse, (b) plasma source rf burst, and (c) high voltage pulse applied to implantation target.

3. Energy spectra of the (a) North Star Research Corporation and (b) Los Alamos National Laboratory plasma source ion implantation modulators.

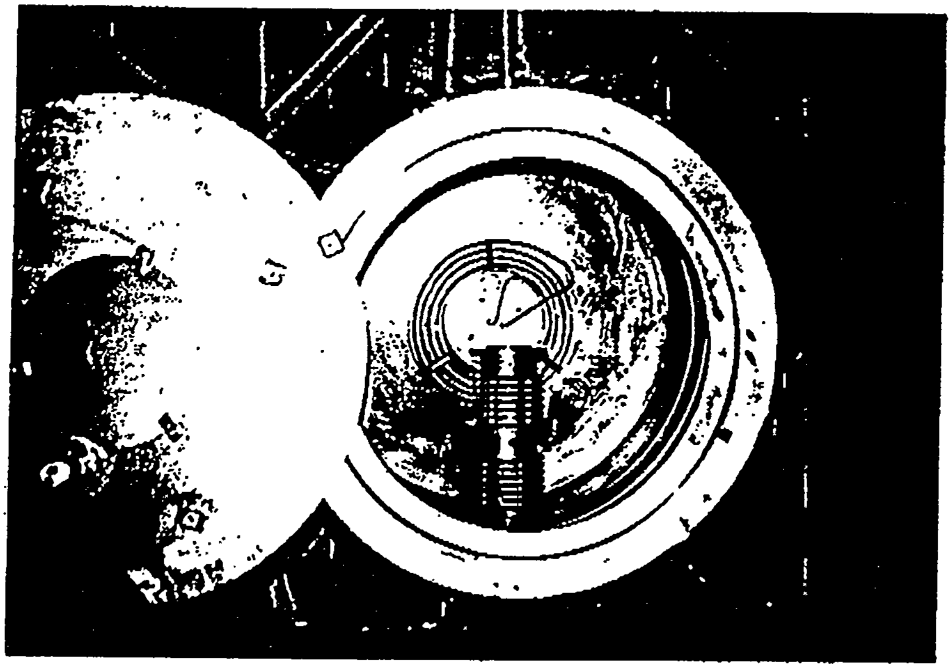

Figure 1

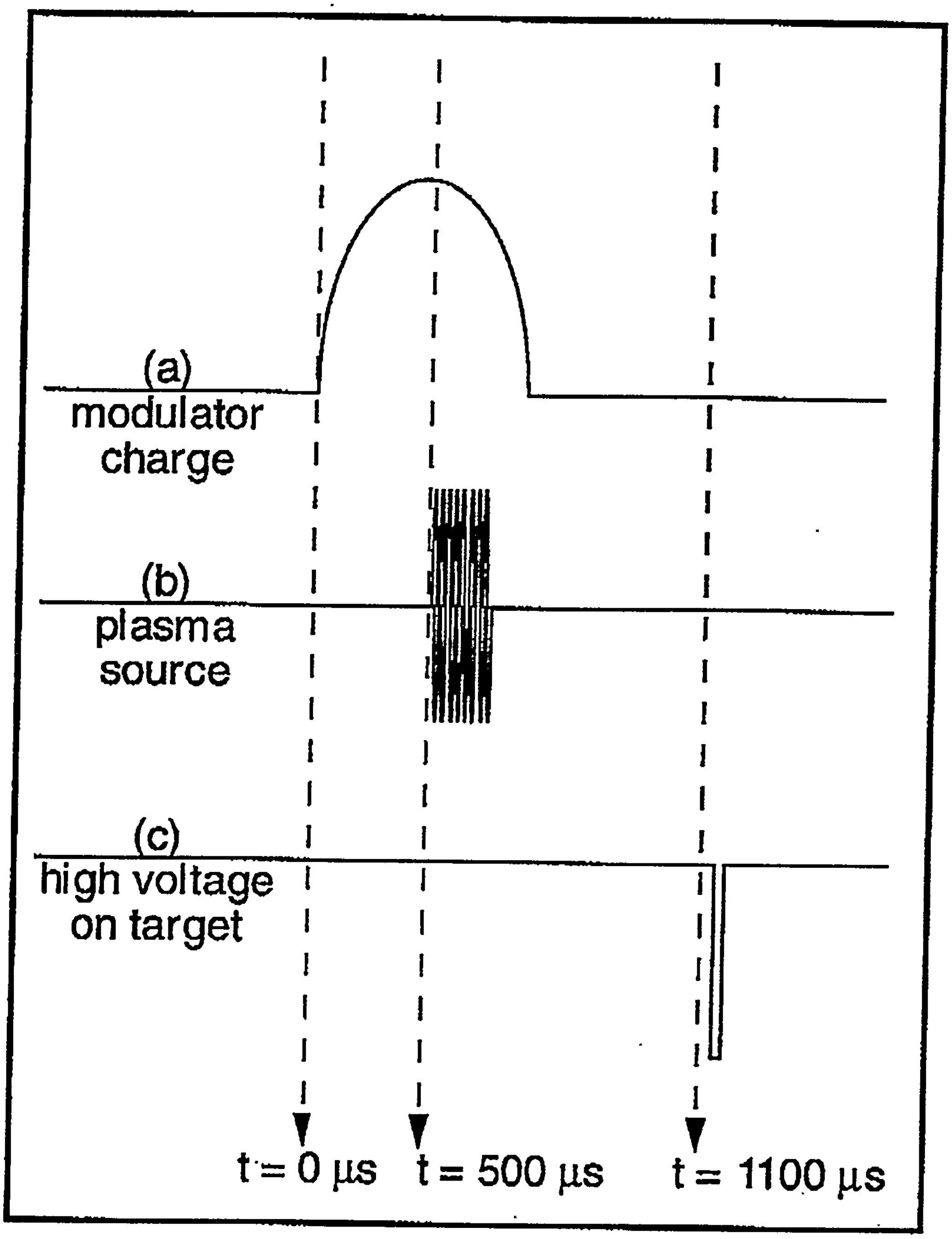
(a)
modulator
charge
(b)
plasma
source
(c)
high voltage
on target
t = 0 µs
t = 500 µs
t = 1100 µs

Figure 2

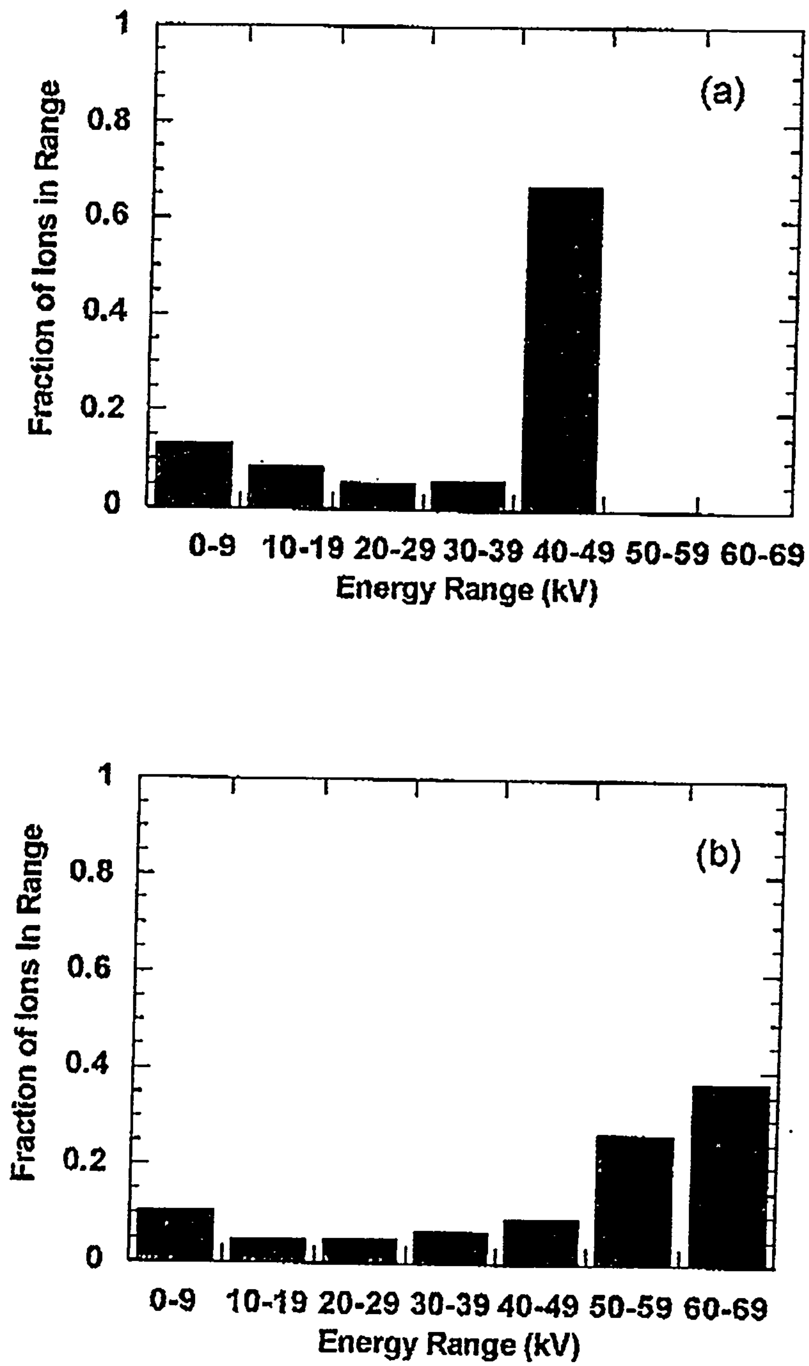
(a)
Fraction of Ions in Range
1
0.8
0.6
0.4
0.2
0
0-9
10-19
20-29
30-39
40-49
50-59
60-69
Energy Range (kV)
(b)
Fraction of Ions In Range
1
0.8
0.6
0.4
0.2
0
0-9
10-19
20-29
30-39
40-49
50-59
60-69
Energy Range (kV)

Figure 3