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CRITERIA FOR PLASMA SOURCE ION
IMPLANTERS**

Author(s):

W. Reass

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OPTIMAL PULSE-MODULATOR DESIGN CRITERIA FOR PLASMA SOURCE ION IMPLANTERS

WILLIAM REASS
LOS ALAMOS NATIONAL LAB, LOS ALAMOS, NM 87545

ABSTRACT

This paper describes what are believed to be the required characteristics of a high-voltage modulator for efficient and optimal ion deposition from the "Plasma Source Ion Implantation" (PSII) process. The PSII process is a method to chemically or physically alter and enhance surface properties of objects by placing them in a weakly ionized plasma and pulsing the object with a high negative voltage. The attracted ions implant themselves and form chemical bonds or are interstitially mixed with the base material. Present industrial uses of implanted objects tends to be for limited-production, high-value-added items. Traditional implanting hardware uses the typical low-current (ma) semiconductor "raster scan" implanters. The targets must also be manipulated to maintain a surface normal to the ion beam. The PSII method can provide "bulk" equipment processing on a large industrial scale. For the first generation equipment, currents are scaled from milliamps to hundreds of amps, voltages to -175kV, at kilohertz rep-rates, and high plasma ion densities. When objects immersed in a plasma are pulsed, a space-charge layer of ions or "sheath" forms between the objects and the plasma. These ions "fall" across the applied potential and impact normally. As the ions are depleted from the plasma, the sheath expands away from the object. This results in a dynamic and time-dependent load capacitance and resistance. In addition, initial plasma-displacement currents help create an overall load characteristic that is difficult to electrically match efficiently. Plasma (gas) type, density, atomic species, gas mix, target (object) area and geometry, and secondary electron emission also affect load impedance. It would be advantageous to have one modulator system capable of efficiently processing various "product lines." Further problems also arise in that (particle) implant efficiency and product quality are also affected by the HV pulse waveform. A sharp rise time can bury the implant. Too slow a pulse rise or fall causes sputtering, drilling, or whiskers in addition to a reduced implant density. Optimal rise times coupled with the proper plasma density can provide: multiple improvements in deposited dose, a modified deposition density profile, and a smooth finished surface. The resulting calculations from the plasma and network analysis codes will be presented in addition to experimental results that direct a solution toward the optimally efficient pulse power modulator system. The resulting pulse power modulator system outline and overall characteristic will also be presented in addition to suggested hardware configurations for future application.

THE PSII PROCESS

Various organizations are using the Plasma Source Ion Implantation (PSII) process of Conrad [1,2,3]. As shown in Table 1, national and international groups are examining PSII and similar hybrid processes. Improvements in material hardness, fatigue life, wear, corrosion resistance, sliding friction, galling, and electrical and optical properties can be realized in just about any component, whether metal, ceramic, or plastic. Recent published efforts detailed results with cutting tools, stamping tools, draw dies, ball bearings, orthopedic devices, automotive, and aerospace components.

"Open" research summary results are most typically reviewed in the "PSII Newsletter" published by University of Wisconsin (UW). The UW newsletter has reviewed film coating of M2 and A2 implanted steels, among many other process results. Field tests of A2 tool steel have shown improvements in life span by almost a factor of two (14 million hits) in the manufacture of aluminum cans. Field testing with M2 punch punches of tool life by coating implantation, with a 100% increase in life span. Field tests of M2 punch punches of tool life by coating implantation, with a 100% increase in life span.

with lifetime increases of better than 10 times. In addition to the typical gaseous implants (e.g. nitrogen for "nitriding"), two hybrid processes have been developed: "Ion Beam Mixing" and "Ion Beam Enhanced Deposition" [4]. In these processes, material is deposited on a substrate by physical vapor deposition or chemical vapor deposition using the PSII process to integrate the coating into the substrate and to additionally alter the coatings character. It is known that metallic implants can also provide significant improvements to various substrate materials.

TABLE 1. PSII RESEARCH PROGRAMS

GROUP	STATUS
University of Tennessee	Operational
Northeastern University	Operational
General Motors Research Lab	Operational
Los Alamos National Lab	Operational
Hughes Research Lab	Operational
CSIRO/ANSTO-Australia	Operational
Varian Associates	Operational
Dalian University, Peoples Rep. of China	Operational
Harbin University, Peoples Rep. of China	Under construction
Inst. Nuc. & Solid State Physics, Germany	Under construction
University of Natal, South Africa	Operational
Applied Materials/UC-Berkeley/LBL	Operational
University of Wisconsin	Operational

PSII PHYSICS

When an object is immersed in a plasma and pulsed with a high negative voltage, the motion and displacement of the plasma electrons and ions partially determine the characteristic load impedance. Plasma type and density, object geometry, and secondary electron emission also significantly affect impedance. Second order effects can also (slightly) change the dynamic loading. These second order effects include the ionizing power, which additionally alters atomic species [5], and plasma density. The material composition of the "work piece" also has a marked and dramatic effect on load impedance, due to the work piece's secondary electron emission coefficient. For a given plasma density and type, various objects would present different dynamic loads. These various properties not only give rise to a time-dependent load characteristic, but also to the process parameter characteristics. If the object is at instantaneous voltage rise, the ion sheath expands as shown in the figure 2. At time "t=0," a neutral plasma surrounds the work piece. At time "t=t1," Figure 2.2, the electrons from the plasma have been repelled in the vicinity of the work piece for a time interval (~6 ns) comparable to the inverse of the plasma electron frequency. At this point, the massive ions have been "uncovered" to a distance equal to the "initial ion matrix sheath" [6]. The massive ions are then accelerated into the target, resulting in a large surge current, for a period related to the plasma ion frequency (1-2µs). When the ion matrix has been slightly depleted, the plasma is in equilibrium with space-charge limited ion flow (fig. 2.1), sheath expansion (fig. 2.2) for the remainder of the pulse, maintaining a constant continuity laws [7]. The ion matrix current density is an order of magnitude greater than the ion flow.

PLASMA DYNAMIC IMPEDANCE

The plasma dynamic resistance is a function of the ion flow, the space-charge limited ion current, sheath expansion, and secondary electron emission. The plasma sheath resistance for a 100 pps pulse is given by a singly ionized plasma is given by

$$R_p = \frac{1}{\epsilon_0} \left(\frac{1}{\omega_p^2} \right) \left(\frac{1}{1 + \frac{1}{\omega_p^2}} \right)$$

PLASMA EVOLUTION DURING PULSE PHASE

FIGURE 3

where M is the ion mass, V is the sheath voltage, n is the plasma density, A is the implant area, ω_{pi} the plasma ion frequency, and t is time. The secondary electron emission coefficient γ depends on ion energy and object composition and can be approximated for most cases of interest by

$$\gamma \approx (dV)^{1/2} \quad (2)$$

where the coefficient A depends on surface composition and ion implant species. The ion plasma frequency, dependent on ion density and mass is determined by

$$\omega_{pi} = \left(\frac{n_i e^2}{\epsilon_0 m_i} \right)^{1/2} \quad (3)$$

Although the above equations are derived for planar geometry, they give an appreciation for the type of time varying load that can be expected for an actual 1-D object. A circuit simulation (planar geometry) of the load resistance as a function of time after space-charge-limited Child-Langmuir flow has been established is given figure 3. In this simulation the plasma density is $10^{18}/\text{cm}^3$ with a target area of 10^4 sq. cm . The secondary emission coefficient γ , is 10 (40kV) with a 25 amp maximum total current.

A 1-D particle-in-cell simulation (Figure 4) of the plasma implant current includes the large initial current surge from displacement current and the depletion of the ion matrix [9]. Simulations for three plasma densities are plotted for a 60 kV pulse voltage and a γ of 17 (60kV).

The plasma sheath capacitance is also a time varying effect dependent on applied voltage, particle density, and plasma ion frequency. The vacuum capacitance of a planar expanding sheath is given by

$$C_p = A \left(\frac{\epsilon_0 m}{2V} \right)^{1/2} \left(1 + \frac{2}{3} \omega_{pi} t \right)^{-1/2} \quad (4)$$

In early time, the effective plasma sheath capacitance can be higher by a factor of two due to the uniform ion matrix region. Typical load capacitance may vary from 500 to 1000 pF early in time to about 10 pF late in time. The modulator must also account for stray and transmission capacitance.

MODULATOR TIMING CHARACTERISTICS

Other factors that may affect modulator timing characteristics are the applied pulse width and repetition rate. The desired pulse width is determined by factors involving plasma ion density, vacuum chamber dimensions, and work piece size. The plasma ion density is determined by fill pressure and ionization power. A higher ion density results in a sheath that propagates at a higher rate. The difference in dimension between the work piece and vacuum chamber wall determines the volume available for sheath expansion. Higher ion density and large object features with greater sheath expansion will permit longer pulse widths. A major consideration is the E-field profile across the sheath. Sharp objects do not like a sheath in the presence of high plasma ion density, which can result in arcing and sputtering. It seems that for the present and probably future operational systems, a pulse width width is compatible with work piece features, ion density, and vacuum chamber dimensions. It is convenient that most high power switches are also compatible with this pulse width. The maximum repetition rate (of the plasma) is determined by the depleted sheath volume, ion density, ion density, modulator current and pulse width, and rate at which the plasma ions can refill the depleted volume. The plasma ambipolar diffusion coefficient, which partially determines refill time, is a function of the ratio of electron to ion temperature. As a resultant calculation, a graph of the maximum repetition rate for 1 eV ions, is given. Desirable implants would have sheath expansion as small as possible (20 cm or less) and a high ion density conservative E-field intensities to maintain sheath stability. Maximum repetition rates are realized in the 2 to 5 kHz regime. Repetition and rep. rates, repetition rate.

higher switching currents (and <I>), all lead themselves to a higher production throughput rate.

FIGURE 5: Plasma Refill Time (T_r , 1eV)

MODULATOR DESIGN REQUIREMENTS

For a production-oriented industrial environment, reliability, amortized system cost, flexibility, and electrical efficiency are important considerations. To insure a reliable modulator system, a system design using an evolutionary hardware configuration can provide a modern design with components of characterized performance with predictable lifetimes and failure rates. Revolutionary hardware configurations must be approached cautiously and be carefully developed to determine actual operational and lifetime characteristics before utilization in a production environment. It is desirable for the modulator and high-voltage system to appear as reliable and transparent as the AC utility! The modulator and HV system should not require a fleet of technicians or constant surveillance! Due to the relatively high rates and the required (long) component lifetimes for a reduced amortized system cost, pulse-rated components must be avoided. A typical pulse-forming network (PFN) capacitor has a 1E9 pulse lifetime, resulting in a failure in about twenty days at a 2 kHz repetition rate. A typical thyristor-switched PFN is questionable, not only because of the limited capacitor life but also because of the required impedance match for efficient operation. Any mismatch results in power being delivered to the end-of-line clipper. Swamping resistors used in an attempt to equalize the impedance variation impact efficiency. It is desirable for the modulator to be capable of varying pulse width, frequency, voltage, and current. This would provide a flexible design able to operate in various component processing modes and not be tied to a particular or fixed (obsolete) PFI procedure. Component PFI process improvements can be made that would be transparent to the modulator and HV system. This type of flexibility can be provided by various classes of switch tubes. To maximize system efficiency, circuit topology must be examined carefully. For example, fault current limiting components can severely reduce system efficiency. A low-voltage design with a pulse transformer must be examined in detail due to increased primary PFN switching losses. In addition to transformer core losses, vacuum switch tubes have the same rate of voltage drop, whether at high voltage or low. It is the authors' opinion that gridded switch tubes are questionable at the voltages and currents of interest (20A @ 50kV and above) because they are cumbersome, inefficient, and not intensive, and their operation. High current and high voltage gridded switch tubes are large and typically require special features and shields. They are not typically optimized for arc immunity, which reduces system size and external to the plant facility. Filament power can be large (up to 50W) and put further requirements on the plant facility. Special precautions must be utilized in order to protect the tube grids in the event of arc-down. Gridded tubes can lose hold-off ability due to whisker growth on the grid meshes after an arc-down.

Another important design consideration is fault modes and system protection. Systems that utilize series swamping resistors to limit fault currents also sacrifice efficiency. A typical and frequent fault (especially during initial "start-up") would be an arc-down of the object. Some switching devices have a current-limiting effect or may latch-up. Several design considerations or circuit topologies must be utilized to insure overall system safety. Hard-vacuum switch tubes have a large dynamic impedance that limits fault current to a similar value to that being switched. Regardless of the circuitry, energy must be removed (quickly) from the object to prevent whisker growth or drilling. If a hard-vacuum series switch is utilized, it may be simply turned off, without shorting the system. Another fault that must be considered is a "shoot-through" fault, a direct short through the switching network and the object to ground. Fault protection for this mode must include additional circuitry to quickly discharge any stored energy and remove primary (power supply) AC power. Full AC current from the power supply short-circuit current (impedance-limited) must be considered, as fault time scales are significantly longer, and stored energy can impart a greater energy deposition to the object.

THE LOS ALAMOS MODULATOR

The Los Alamos modulator system is designed for large area implants (>1 sq.m) with voltages greater than 50 kV. Although presently operating at 50 kV, a 100 kV power supply should be on-line within 1 year. The initial Los Alamos modulator and high-voltage system utilizes a more evolutionary design. We have chosen a modulator design using a pair of Litron L-1044 cross-field hollow-beam amplifier tubes as a series switch from a small capacitor bank. These hardware elements are well characterized in military radar and particle accelerator service. Cataloged literature have typically been in the 20,000 to 50,000 pulse lifetime. Important characteristics of the L-1044 (a 1044 family) are its pentode like transfer tube, which limits any object arc-down current to a few amperes. The input control element (modulator) is high μ (gain) and virtually non-intercepting to the electron beam because of the tubes cross-field design. The cathode is shielded from high voltage (arcs down will not strike the cathode) which permits the efficient use of oxide cathodes (7% wear rate). The L-1044 has a design limit of 150 kV and a 1 A anode current. Unfortunately, these amplifier tubes have a relatively high voltage drop (10kV) and therefore the system efficiency is less than 50%. It is the authors' opinion (of this design) that has been optimized for arc-down switching service, could have a significantly lower voltage drop. The simplified block diagram of the initial Los Alamos modulator system is shown in Figure 6. The series switch tubes are in a "shoot-through" configuration with power provided by an AC power transformer and control by fiber optic signals. A fault condition, diagnostic monitoring provides signals that determine the appropriate action for the switch tubes or shut down the power supply. Note that there are no fault current energy transfer is limited in the switch tubes to the object in a "shoot-through" fault condition. The series resistance in the capacitor bank (arc-down) is shown. Because of the small capacitor bank, the power supply impedance, energy transfer is limited to both the object and switch tubes. The energy from power supply follows the current path to the object, at most, 4 kV. The initial goal of the Los Alamos PFI system began in May 1980. A typical pulse waveform as shown in Figure 7. A photograph of a complete system is shown in Figure 8. The implant current peaks at 20 A and the voltage approaches 50 kV. The pulse width is 100 ns. The object is a 10 cm diameter. The object is in the switch tubes.

The poor fall time is due to plasma sheath expansion, which increases the dynamic impedance. The slight rise in voltage is due to the AC dynamic impedance of the switch tube coupled with the effect of the increasing plasma resistance. The poor fall time will be improved with the addition of a "tail biter" that discharges the object and transmission capacitance at the end of the pulse. The tail biter is not in our system but will be added in the future. Improvements in rise time can be realized with increased switching currents from hardware upgrades.

FIGURE 6:
Simplified Block Diagram of LANL PSI Modulator

FIGURE 7:
Scope Photo of Modulator Output at 500 Hz Rep Rate

CONCLUSION

The PSI program is an exciting field for the industrial use of pulse modulator technology. The modulator must operate over an extremely wide range of load impedance, from almost a short circuit early in time, to many thousands of ohms, late in time. Optimal design data requires must not only examine various types of switching devices but also fault modes and failure currents. Overall, system complexity must be minimized in addition to utilizing long life components for lower amortized system cost. System reliability and performance are and must continue to be improved as the technology advances.

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