DESIGN OF A 100 KV, 200 AMPERE, 2 KILOHERTZ, SINGLE "HOBETRON" TUBE MODULATOR FOR INDUSTRIAL PLASMA SOURCE ION IMPLANTATION APPLICATIONS*

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ABSTRACT

This paper presents an advanced Plasma Source Ion Implantation (PSII) modulator system which takes advantage of a novel high power electron beam switch tube called the "Hobetron" (derived from *hollow electron beam*). We will describe this tube and outline features which render it so well-suited for use in PSII modulators. The Hobetron has been developed from similar beam switch tubes of proven reliability, and when coupled with an evolutionary modulator design, should provide a system of long life and reliable operation.

I. INTRODUCTION

PSII and related plasma processes have repeatedly demonstrated improvement of implanted component characteristics. Improvements in surface hardness, wear rate, and friction are typically realized in addition to other parameters (e.g. corrosion rates and galling). To further the industrial application of plasma processes, the Department of Commerce has supported developmental work involving industrial, university, and national labs through the Advanced Technology Program (ATP). This partnership includes General Motors, Boeing, DuPont, Litton, the University of Wisconsin, Los Alamos National Lab, and others, to develop the appropriate hardware and process recipes for commercial applications. The various recipes require modulators that can operate at nearly any desired voltage (<100 kV) with a time-dependent load impedance determined by pulse duration, plasma density, plasma species, implant area, implant material, and other numerous effects. Implant (re-treated) objects from the production line (e.g. stamping dies), may be contaminated with oil or release agents. Residue from this material frequently remains on the dies and must be sputter cleaned, preferably by the same modulator used for implantation. The cleaning procedure can cause significant arcing and the modulator must control this behavior to limit arc energy and possible work-piece damage. During the normal implant procedure, work-piece arcs can also be prevalent.

Vacuum tubes are reliable devices for this application since they can operate at nearly any voltage, load impedance, pulse width, and duty cycle. Their constant

current characteristics limit fault current to that set by the "grid" or "mod-anode" voltage. A newly developed tube, the Hobetron,** is an ideal switch tube for PSII use. This device utilizes a circular strip tungsten matrix cathode with a concave (pierce-gun) cross-section. On each side of the cathode is a non-intercepting mod-anode. The straw-shaped hollow-beam flows into a double-walled "Faraday Cage" depressed collector (also circular). This minimizes the electron impact energy, reducing conduction loss (voltage drop). Further, the depressed design maintains a relatively constant beam impact energy density regardless of voltage. The design of this tube permits a transient voltage hold-off of 200 kV, about twice the "DC" rating. Finally, the true constant current characteristics of the Hobetron permit simple and reliable control circuitry to quickly terminate load arcs.

II. PSII MODULATORS

Various PSII modulator topologies have been utilized in past years. Systems have been built with gridded tubes, crossatrons, beam switch tubes, thyatron, and transistors. Most of these systems have been used in small research machines. Even with the limited power required of these systems, trade-offs between the technologies are evident. Crossatrons were difficult to drive at kilohertz frequencies, requiring robust thyatron drivers, and were subject to latch-up in plasma arc-down situations, damaging the work-piece. Unfortunately, crossatrons are not commercially available at the time of this writing. Thyatron switched PFN's have also been utilized, but require careful matching to the plasma load to prevent after-pulses and work-piece sputtering (and implant damage). In addition to sputtering from PFN mis-matches, plasma-arcs will also cause the remaining energy to ring back into the work-piece. Work-piece clipper diodes are then required to prevent reverse voltage pulses. The trained and qualified manpower efforts required to match network operation to plasma conditions, which would change from step-to-step, is not conducive to an industrial process environment. The PFN's more complicated command charge systems and bias transformer reset networks also compromise system reliability and cost. High rate operation is another complication for thyatron

switched systems. The typical thoriated tungsten gridded tube modulator has also found significant use in PSII systems. In the small R&D system, these modulators are simple to engineer and tend to be very reliable. Unfortunately, the tubes can de-condition from plasma-arc downs and their electrical efficiency suffers from high filament and grid drive power requirements. A large PSII system designed with high-power and high-voltage gridded tubes is certainly possible, but these tubes are not tailored for short-pulse application. These tubes are designed for induction heating, broadcast service, and long pulse (e.g. neutral beam) scientific applications. The filaments can require ~5 kW for a (low current) 100 amp tube. Control grid and screen grid power is significant due to their intercepting design. There is an additional complication of the screen grid (crowbar) protect circuits. These tubes are also not well suited for oil immersion and would require high oil flow rates around the filament terminals to ensure proper cooling and prevent oil carbonization. The regions of negative grid impedance have made these tubes subject to spurious oscillation in series modulator service. Transistors have also been demonstrated for small PSII systems but have required extensive snubbing and protection circuitry to ensure robustness. These systems have operated in the 20 to 50 amp regime with low rep-rates and low voltages (<15 kV). Higher voltage and current IGBT series strings have been utilized recently but do not seem to meet reliability, rep-rate, or the voltage requirements of an industrial system. These systems have yet to operate reliably above 15 kV and have been extremely expensive to purchase and maintain. The large component count of series strings, related costs, rep-rate limitations, and questionable reliability have not endeared their use yet.

One of the longest operational PSII modulator systems, and other reliable modulator systems, have used Beam Switch Tubes (BST's). The larger (L-5097) 100 Amp BST has demonstrated lifetimes of over 70,000 hours continuous operation (decades!) at 600 Hz and 160 kV driving accelerator klystron loads (60 Amp per klystron). The smaller 30 amp tubes (L3408) are also being used for klystron modulator service in addition to PSII systems. These systems are of more recent design, but have already demonstrated many thousands of hours of reliable operation. The series BST switched modulator is a simple topology and is easy to design with a minimal part count. The non-intercepting (low current) mod-anode is robust and there are no regions of negative impedance. The internal design structure shields the cathode from (internal) arcs. The tubes constant current characteristics limits (work-piece) fault current to that dictated by the mod-anode control voltage. These tubes are well suited for small PSII systems and could easily be paralleled for large industrial systems. Fortunately, a higher current and more economical BST device is now available, the Hobetron.

III. HOBETRON PSII MODULATOR

The Hobetron series switch tube modulator is configured as shown in Figure 1. The AC utility feeds a T-R set

located on an outdoor pad. The SCR controller, star-point or otherwise, used for system voltage adjustment, is best located indoors and out of the weather for long term reliability. The modulator tank, located next to the process vacuum chamber, contains the remaining PSII modulator system hardware. This includes a DC filter bank with appropriate safety dump switches, the hot deck and Hobetron, and the output diagnostics and termination networks. This simple configuration helps minimize system interconnects and reduces the possibility of ground loops and EMI concerns. A view of the Litton M-786 modulator is shown in Figure 2. The filter bank and hot-deck isolation transformer can be viewed in the foreground. For early modulator testing and evaluation, a single L-5097 with required solenoid system is being installed. The mod-anode drive assemblies are located in the right hand background. When testing is completed, the L-5097 and solenoid system will be removed. Two L-6026 Hobetrons can be installed (L-6026 does not require a solenoid system) to provide a 400 ampere compliance, adequate for almost all process recipes known at this time. DC holdoff in the Hobetron is 125 kV, and in excess of 200 kV for transients, providing a comfortable tube safety margin from work-piece arc induced voltage reflections. The minimum voltage drop of the Hobetron operating at 200 Amps is about 4.5 kV. The filament power is 800 watts, trivial compared to the net power switched. The size of the 40 Megawatt capable, 2 kHz modulator is 5 ft x 5 ft x 6 ft tall.

FIGURE 1: HOBETRON SERIES SWITCH MODULATOR

FIGURE 4: ZOOM VIEW OF CATHODE AND MOD-ANODE ELECTRON DYNAMICS

FIGURE 5: THE L-6026 HOBETRON

IV. HOBETRON TUBE

The mechanical layout of the L-6026 Hobetron is shown in Figure 3. Although somewhat difficult to see clearly, the cathode assembly is centrally located. It has a pierce gun concave cross-section and forms a complete circle around the tube axis, forming a ring. On each side of the cathode, also circularly symmetric, is the mod-anode. A shield assembly, between the mod-anode and collector, provides arc protection and additionally acts like a screen grid to reduce feedback (Miller) capacitance. The double-walled (for cooling) "Faraday Cage" depressed collector also helps to provide a field free region for the electron beam to spread out and reduce electron impact energy. This has the effect of reducing tube voltage drop, increasing efficiency. This design also provides for a more even impact energy distribution within the collector, minimizing the probability of hot spots and resulting shoot-through. A zoom view of the cathode and mod-anode beam dynamics in Figure 4 show no mod-anode electron intercept at 200 Amps with the tube in saturation. A view of the Hobetron is shown in Figure 5.

IV CONCLUSION

A modern, compact, and efficient modulator system has been tailored to a newly developed switch tube. The modulator system and switch tube are nearly completed and will soon ship to the Beta site manufacturing facility for PSII industrial processing. It is important to note, that among the various modulator technologies and methods one can utilize for PSII processing, the ATP program has selected this topology to reliably accomplish PSII in an industrial environment.

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**Litton Patents Pending