A DECADE OF SOLID STATE PULSED POWER DEVELOPMENT AT CYMER INC.

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Abstract

This paper will summarize over 10 years of solid state pulsed power development at Cymer Inc. associated with power systems for excimer and other light sources used in the application of semiconductor photolithography. Over eight different generations of power systems have been designed and implemented as the light source systems themselves have evolved over time. Each of these power systems includes a charging system and a solid-state switched magnetic pulse compressor. Specific technical challenges and accomplishments will be described for each iteration. In addition, application specific requirements will also be discussed including high volume manufacturing, high reliability, long lifetime, large operating range, compact size and weight, ease of troubleshooting, high efficiency and effective thermal management, low cost, safety, and third party approvals (UL and TUV).

I. INTRODUCTION

Cymer is the world's leading supplier of excimer light sources for semiconductor photolithography and was formed in 1986. From then until 1995, production light sources utilized a simple energy storage capacitor and thyratron circuit to provide the pulsed high voltage necessary for generating the light source discharge. In the early 1990's, a DARPA contract to Dan Birx allowed development of some components of a Solid State Pulsed Power Module (SSPPM) and transfer of this technology to Cymer. As of Q1 2004, 2282 Cymer light sources were installed worldwide, virtually all of them with SSPPM units. Over 3800 SSPPM sets have been manufactured since 1995 (including a large fraction for light source system upgrades and for spares).

SSPPM hardware, utilizing solid-state switching and magnetic pulse compression, has several huge benefits over thyratron-based units. While thyratron tubes have finite lifetimes of a few billion shots, the SSPPM units have virtually infinite lifetime. Recovery of the energy reflected by the load eliminates streamers normally occurring late in the discharge, which limit the light source chamber lifetime [1]. Because of fewer replacements and the elimination of warm-up time (necessary for the thyratron) after any maintenance, there is less impact on semiconductor fab (fabrication facility) operation. Finally, pre-fires and missing pulses are avoided so that wafer level rework is not required.

II. GENERAL DESIGN ISSUES

In addition to the pulsed power requirements for these SSPPM units, the application of semiconductor photolithography necessitates other additional demands. Since the modules are produced in relatively high volumes (100's to 1000's of units), a full and complete documentation package is necessary. This includes a full Bill of Materials, part specifications, piece part and assembly drawings, assembly and test procedures, etc. Procurement and manufacturing personnel must be trained on the specific parts and sub-assemblies and how they are integrated. Plans for spares and their worldwide distribution also need to be addressed.

Operation in a semiconductor fab environment demands that the module lifetime be essentially infinite. Since the typical lifetime of a stepper/scanner is on the order of 5 years, this translates into a shot life of at least 25-50 billion shots. High reliability is also a necessity. This is accomplished through sufficient component de-rating and design confirmation through HALT testing, thermal mapping, etc. Testing of the 5000 series SSPPM after accrual of 50B shots (obtained running continuously over 2.5 years) indicated no measurable signs of degradation of any of the major components [2,3].

Where many magnetic modulators have operated in a relatively narrow voltage range, these SSPPMs must function over a much larger range (corresponding to an initial stored energy range of approximately 1.5 to 5.5 J for the excimer light source SSPPM systems). This is necessary since the chamber operating voltage increases with both gas and electrode lifetime. The magnetic switch is therefore designed with sufficient volt-seconds to operate effectively over this energy range.

Since fab floor space is expensive, the modules must be designed for minimum size and weight. Module weights are generally kept to ~100 pounds or less since they may require field replacement. In addition, ease of troubleshooting has to be considered in the design and diagnostics included to aid in that process. Module cost is important since it impacts the company profitability.

Safety, SEMI and third party approvals and compliance (UL 3101-1 and TUV EN 61010-1) must be addressed. Finally, there are also design restrictions on the types of materials that are allowed in the fab environment (insulating impregnation fluids must be minimized and acceptable for use in the fab, flammable materials must be minimized, etc).

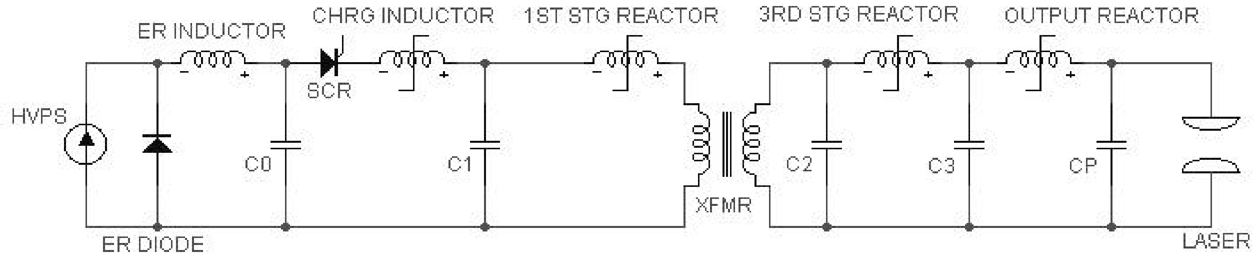

Fig. 1. Simplified Schematic Diagram of 5000 Series SSPPM with HVPS and Light source Chamber.

III. 5000/5010 SSPPM

The initial Cymer production SSPPM was developed for introduction in the 4000F (600 Hz, 6 W KrF) and 5000 series (1000 Hz, 10W KrF) light sources. These units were designed to operate at rep-rates of up to 1 kHz. Figure 1 shows a simplified electrical schematic diagram of the 5000 series SSPPM. The power system is divided into three modules, a High Voltage Power Supply (HVPS), Commutator, and Compression Head. Approximately 1.5-4.0 J was initially stored in the first storage capacitor of the Commutator at a voltage of 550-800 V. Parallel SCR switching, a 26X inductive voltage adder transformer, and three stages of magnetic pulse compression were used to generate the ~12-19 kV, 150 ns risetime, output voltage pulse to the light source chamber.

Since this was the first design introduced for mass production, numerous issues had to be resolved. Many of these were discussed in the previous section. Specific examples included ensuring consistent production of the magnetic switch cores at multiple (different) vendors' facilities and fixing design errors with a commercial, high voltage connector used on the cable between Commutator and Compression Head modules.

Although thermal management was not a strong issue for this design family, some modifications were required after several initial prototypes revealed that the Compression Head magnetic switch cores were operating at relatively high temperatures. As a result, the temperature caused a reduction in the magnetic material ΔB and this affected the system transfer efficiency. A water-cooled, cold plate was attached to the rear side of the Compression Head housing in order to keep the switch at an acceptable operating temperature. Forced air-cooling, with facility air pulled through the light source cabinet, provided thermal management of the Commutator and HVPS modules.

Because the light source operation requires precise energy control in order to manage the illuminated dose on the IC wafer, the SSPPM must also produce precisely adjusted energy to the light source chamber. The SSPPM itself can accomplish this as long as the initial charging voltage is highly regulated. As a result, there was a significant effort with the capacitor-charging HVPS vendor (KSI) to improve the pulse-to-pulse voltage regulation of the supply to levels of better than $\pm$0.15%.

An additional requirement from the stepper/scanner is that the trigger-to-light output delay be kept constant over the entire operating range. Since the operating voltage of the SSPPM varies over the light source chamber lifetime (increasing as the electrodes wear and the gap increases), some means had to be developed to compensate for different switch-out delays in the magnetic switches as the voltage changes. This was done by inserting an adjustable, additional delay into the low voltage trigger chain of the initial solid-state switch as the operating voltage increased.

The 5010 SSPPM was a design iteration similar to the 5000 series with a faster output voltage risetime (reduced from 150 ns down to ~100 ns).

IV. 6000/6010 SSPPM

The 6000 series light source was designed to deliver 20 W of 248 nm, KrF light (ELS-6000) at a rep-rate of up to 2 kHz. The SSPPM initial energy storage range was increased to 1.5-5.5 J (corresponding to a charging voltage of 600 – 1150 V) in order to extend the light source energy vs. voltage range. As with the 5010, the output voltage risetime was 100 ns.

The Commutator design replaced the SCRs with IGBTs allowing faster commutation (reduced from 10 µs down to 5 µs). This faster transfer time, coupled with an improved 1st stage reactor design and a single turn transformer secondary (as opposed to the dual secondary in the 5000 series), led to a 25% faster output risetime for the Commutator.

The improvements to the Commutator enabled significant enhancement of the Compression Head performance, allowing us to remove a pulse compression stage while maintaining the output risetime achieved in the 5010 series design. The resulting design offered an elegant solution by offering equivalent performance while reducing thermal loads and improving system transfer efficiency. This simplification of the pulse power design also had a ripple affect to other SSPPM features. The module weight was reduced by ~30% with the elimination of the compression stage. The required volume of cooling fluid was reduced by 400%. The parts count of each module was reduced offering improvements to cycle times and material management.

The new 6000 light source platform offered us a chance to enhance upon what we'd learned with the initial SSPPM. This allowed us to improve many features of the earlier iteration while still driving for improved performance, higher efficiencies, and lower costs.

The 6000 series also required more attention to thermal management with the higher power levels. Although water-cooled designs are prevalent in pulsed power systems, internal and external resistance prevented us from implementing it on this generation design. As a compromise we continued the use of forced air cooling, and to ensure a consistent source of cooling air, air-to-water heat exchangers were added to the light source frame behind each module. This cooling scheme also allowed us to minimize the thermal interactions between our modules and the other temperature sensitive components (e.g. optics) in the light source system. The most unique implementation of this cooling scheme is associated with the Compression Head design. The Compression Head has a dedicated heat exchanger that re-circulates its cooling air allowing self-contained cooling.

The electrical and mechanical design of the pulse power system was also addressed to further enhance reliability and serviceability. For example, mechanical connections between the Compression Head and light source chamber were simplified to reduce the number of fasteners and still maintain excellent electrical connections.

Additional improvements were performed on the timing compensation circuitry, reducing the typical variation of the trigger-to-light delay down to $\pm$50 ns [4]. This provided significantly more margin for a technical specification that sometimes required more adjustment time in manufacturing on the 5000 series SSPPM.

The 6010 SSPPM was a minor derivative of the 6000 version and was designed to operate at slightly lower output energy per pulse at rep-rates of up to 2500 Hz, maintaining the same overall average power capability.

V. 7000/7010 SSPPM

Cymer developed the 7000 series light source product line to operate at rep-rates of up to 4 kHz. The KrF version (ELS-7000) would generate 30 W of 248 nm light while the ArF version (Nanolith 7000) would provide 20 W of 193 nm light. In addition to the higher light source output power levels, this generation also delivered further improvements in narrower bandwidth. The output voltage level was increased and the risetime reduced from 100 ns down to 60 ns, both in order to improve the light source operating range and conversion efficiency.

Because of the higher rep-rate, timing in general was an issue of the 7000 SSPPM development. The higher rep-rate also implied a higher average power level with the corresponding needs for more thermal management.

The total inter-pulse timing period is divided up into a number of different segments and apportioned to several different tasks. Because the light source typically operates in a constant energy mode, the voltage is adjusted from pulse to pulse in order to maintain the same light energy output. A substantial amount of time is therefore required to read the light source pulse energy detector and calculate the high voltage setpoint for the next pulse in the controller software algorithm. In addition, the power system time is also broken down into different segments for charging, discharging and pulse compression, and energy recovery. As the inter-pulse time dropped with the increase in rep-rate, the time allowed for these other events could not be reduced in proportion to the reduction in inter-pulse time. As a result, the time allowed for charging was decreasing faster than that due to just the rep-rate increase. Capacitor charging HVPS modules therefore became prohibitive at this stage since the required charging rate was increasing at a rate faster than the increase in rep-rate.

The solution to higher rep-rate charging was found in the form of resonant charging. Figure 2 shows a simplified schematic diagram of the 7000 SSPPM along with the HVPS and Resonant Charger (RC) modules. In this case, a HVPS simply maintains the average voltage on a large filter capacitor (C-1) and a charging switch along with a resonant charging inductor discharges small fractions of the total stored energy in the filter capacitor in order to resonantly charge up C0 in the SSPPM. The SSPPM can therefore be pulse charged very quickly in order to satisfy the high rep-rate operation requirements while the HVPS can simply provide a steady-state flow of power to maintain the filter capacitor voltage. Tight voltage regulation is controlled through an energy calculator circuit that opens the charging switch when sufficient energy is stored in the C0 capacitor and the RC charging inductor. A De-qing switch is also used to terminate the charging once the target voltage is achieved. Since resonant charging also provides a voltage step-up, the HVPS output could be less than that required of the SSPPM. In this case, the input voltage of the SSPPM was 750 – 1450 V and the HVPS output was fixed at 800 V.

The 2X increase in rep-rate required improved cooling of all the modules. For this generation design, water-cooling was implemented as the primary means of removing heat although air-cooling was also used to support the thermal management. Water-cooled, cold plates were used to remove the heat from the semiconductors (IGBTs and diodes) in the HVPS, Resonant Charger, and Commutator modules. Heat from the 1st stage reactor magnetic switch was transferred into the Commutator cold plate.

A unique design was developed for cooling the output reactor magnetic switch in the Compression Head module. In this case, the reactor housing is cooled directly with water using a loop of copper tubing attached to the housing. A solid, continuous tubing section avoids any joints inside the module sheet metal cover and reduces the potential for any water leaks. The copper tubing also provides the electrical return path for bias current supplied to the output reactor.

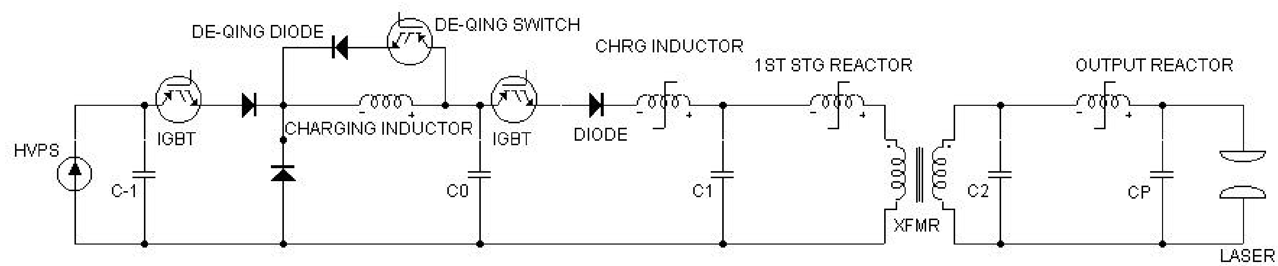

Fig. 2. Simplified Schematic Diagram of 7000 Series SSPPM with HVPS, Resonant Charger, and Light source Chamber.

Since the reactor housing is at the full output voltage, some means must be used to prevent the copper tubing cooling lines from shorting out the output pulse. As a result, the copper tubing is wound around a ferrite core to provide inductive isolation.

An internal fan in the Compression Head provides some forced air-cooling of the remaining components (e.g. capacitors and the other bias isolation inductor). FEA thermal analysis has been done on models of the output reactor assembly and validated with actual measurements taken using fiber optic temperature sensors imbedded in the magnetic cores. These tools are now being used for additional future development efforts.

The 7010 series SSPPM now entering production has the same electrical specifications as the 7000 version. Changes were made primarily to realize cost reduction.

VI. XLA SSPPM

As noted earlier, the requirements for a lithography light source are continually increasing in power and decreasing in bandwidth. It is prohibitive to achieve this by simply increasing the pulse rep-rate due to several issues including electrical-to-light conversion efficiency and the power needed for the light source chamber blower motor (that is proportional to the cube of the rep-rate) [5].

In 2002, Cymer developed the XLA series light source based on MOPA (Master Oscillator & Power Amplifier) architecture where two separate light source chambers are used. The MO provides the extremely low bandwidth required of the final light pulse. The PA amplifies the MO light to produce the required light source power level at 4 kHz rep-rate. The XLA100 (40 W ArF at 193 nm) was the first XLA light source to be developed.

The design approach of the XLA power system requires two SSPPM systems to drive the MO and PA light source chambers [6] with the PA pulse generated 25-50 ns after the MO pulse so that the PA chamber is energized with the arrival of the MO light pulse. Since the light source output efficiency is extremely sensitive to this timing, these two pulses must be synchronized to within ±5 ns.

Figure 3 shows the simplified schematic diagram of the MOPA SSPPM system. The SSPPM design was largely derived from the 7000 SSPPM although it was modified to meet the specific light source requirements and the technical issues that drove them, which are addressed below.

One can see from Figure 3 that we use a single Resonant Charger driving two Commutators and the two subsequent Compression Heads and chambers. This approach guarantees that the timing difference due to charging voltage variations is minimized since both SSPPM systems are charged to a common voltage level, thus eliminating the largest potential source of timing jitter between the MO and PA.

The tight timing requirement must be met over all operating conditions. The operating voltage of these light sources can vary between 800V and 1200V over the lifetime of the light source chamber. The tight requirement of the light source energy dose mandates that the voltage also be adjustable from pulse-to-pulse within a range of ~30V in order to compensate for light pulse energy variations. As a result, the light source controller must compensate the MO-PA delay as the charging voltage changes. For this reason, the regulation of the Resonant Charger must still be adequately controlled. The pulse-to-pulse common mode and differential mode voltage regulation of the Kaiser Systems Resonant Charger output was improved meet these requirements.

Other factors that influence the magnetic modulator pulse propagation delay include the primary switch (IGBT) jitter, bias power supply regulation, and temperature related effects, etc.

A low jitter and drift high voltage IGBT gate driver was developed [7] that minimizes the IGBT turn-on jitter to within 0.58 ns and turn-on drift to within 1.28 ns while operating at rep-rates of up to 6 kHz. This was a significant improvement from the previous IGBT gate driver design using a commercially available IGBT driver that had a significant delay vs. rep-rate function and delay vs. temperature drift. Finally, the bias power supply and circuitry of Commutator 1st stage reactor was modified to meet the ±5 ns of the target jitter specification.

We also developed a magnetic core tester to measure the volt-seconds of the 1st stage and output reactor cores. This enables us to control the volt-seconds of the reactor to within ±5%. This ensures that the light source control module can properly adjust for long-term drift and also ensures that interchangeability of modules in the field for service convenience does not cause an issue or necessitate additional adjustments.

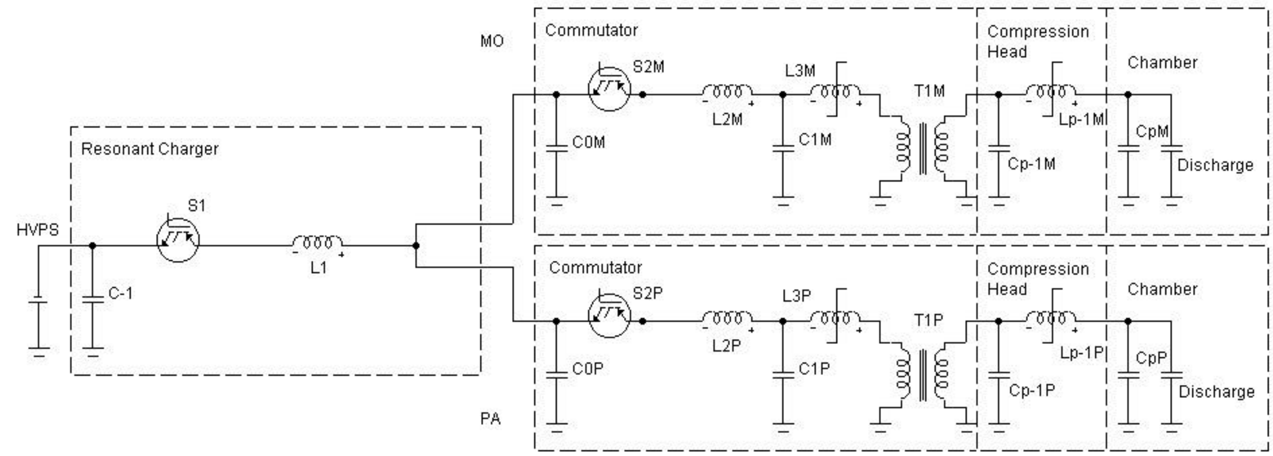

Figure 3. Simplified Schematic Diagram of XLA SSPPM Modules with Common HVPS and Resonant Charger.

Similar to the 7000 SSPPM, both water and air-cooling methods were employed for thermal management and heat removal.

As noted earlier, the light source controller continually adjusts the timing delay between the MO and PA SSPPM triggers in order to maintain the proper target delay necessary to optimize the light source output. This timing is adjusted with operating voltage and also modified as necessary to accommodate for more long-term changes in the SSPPM unit timing delays due to temperature, etc. Figure 4 shows timing synchronization error data from a recent test. One can see that the timing error has been held to less than $\pm$2 ns, well within the system timing jitter budget of $\pm$5 ns. The bi-modal distribution of the histogram is due to the $\pm$0.5 ns dither in the timing delay that is generated by the controller.

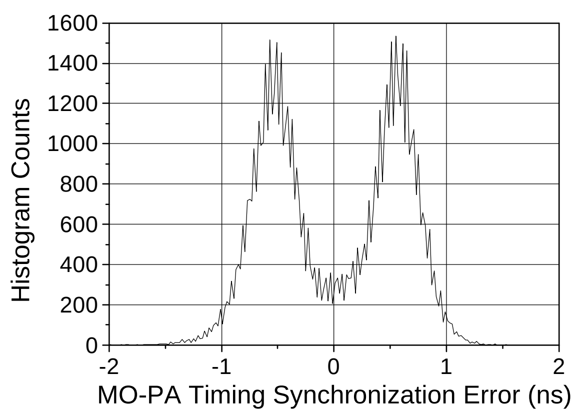

Figure 4. XLA MO-PA Timing Synchronization Error.

VII. EUV DPF SSPPM

SSPPM systems have also been developed for other lithographic light sources besides excimer light sources [8]. In this case, it provides pulsed energy to a Dense Plasma Focus (DPF) device being produced as a potential source of Extreme Ultraviolet (EUV) light at 13.5 nm. While the general topology is very similar to the power systems used in excimer light sources, there are some differences [9]. Figure 5 shows the EUV DPF SSPPM assembly lying on its side. The entire module is 2 feet in diameter and 2 feet in length.

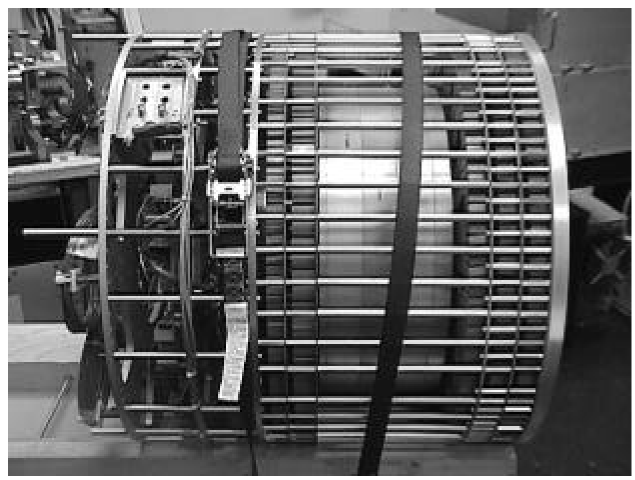

Figure 5. EUV DPF SSPPM Assembly.

The initial energy per pulse in the DPF system can be up to ~20 J. In order to produce acceptable levels of power necessary for projected wafer throughput, this machine will likely have to run at rep-rates approaching 10 kHz. Because of the resulting high average power levels, much of the current engineering effort is associated with thermal management. A prototype machine capable of 5 kHz steady state operation is currently being assembled utilizing liquid cooling hardware to remove heat dissipated within the solid state and magnetic components.

Removing heat without utilizing large volumes of oil or flowing oil through an external heat exchanger has been a challenge. We have also tried extremely hard to implement thermal management designs that do not penalize the saturated inductance of the magnetic switches. The current designs therefore attempt to supply cooling water as close as possible to the magnetic switch cores while minimizing the thermal impedance between the cores and the cooled surfaces.

Higher power density HVPS modules and Resonant Chargers have also been developed as part of this overall effort. A 52 kW, 800 V HVPS module and corresponding Resonant Charger module have been prototyped and are now being tested on several different experiment platforms.

In addition to the SSPPM and thermal management development efforts, work has also been performed to investigate the contributions of various factors in the total lumped output inductance of the SSPPM. Alternate capacitor bank layouts have been investigated in order to maximize the peak output current delivered by the SSPPM since that is thought to have a significant impact on the EUV generation efficiency.

VIII. FUTURE DEVELOPMENT

Development of the SSPPM technology to date has generally followed the trends of increasing rep-rate, increasing output voltage, and faster output risetimes. Higher rep-rates imply higher light source output power levels which allow higher semiconductor wafer processing and throughput. Higher output voltage typically relates to more light source energy per pulse and/or a tighter light source bandwidth (which requires more electrical energy to achieve). Faster output risetimes are often desired since these can translate into better electrical-to-light energy conversion efficiencies

Future lithographic systems will undoubtedly continue to evolve towards even higher rep-rates and higher average power levels. Thermal management will therefore become increasingly important and even more clever means of removing heat from components such as the magnetic switches will be required. Proprietary techniques are already being developed to address these needs and prototype hardware is now being tested on several different power system platforms.

IX. ACKNOWLEDGEMENTS

The authors would like to honor Dan Birx for his significant work in developing and evolving this technology for Cymer and in training us to carry on in his absence. In addition to the authors, Brett Smith, Robert Saethre, and David Johns all contributed towards various SSPPM and power system designs discussed in this paper. Bill Partlo was instrumental in helping to guide the SSPPM development effort and to help optimize the design requirements for integration with the light sources. Terry Houston was responsible for the assembly, and modification of virtually all of the different design prototype modules and provided significant help in troubleshooting and testing. Kaiser Systems and Universal Voltronics developed HVPS and charging system modules in support of these overall efforts.

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