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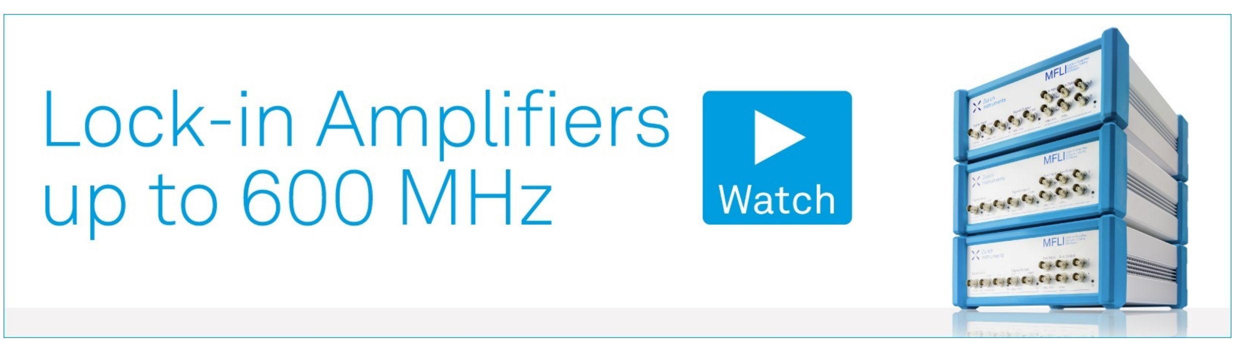

A high voltage pulse power supply for metal plasma immersion ion implantation and deposition

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We describe the design and implementation of a high voltage pulse power supply (pulser) that supports the operation of a repetitively pulsed filtered vacuum arc plasma deposition facility in plasma immersion ion implantation and deposition (Mepiiid) mode. Negative pulses (micropulses) of up to 20 kV in magnitude and 20 A peak current are provided in gated pulse packets (macropulses) over a broad range of possible pulse width and duty cycle. Application of the system consisting of filtered vacuum arc and high voltage pulser is demonstrated by forming diamond-like carbon (DLC) thin films with and without substrate bias provided by the pulser. Significantly enhanced film/substrate adhesion is observed when the pulser is used to induce interface mixing between the DLC film and the underlying Si substrate. © *2010 American Institute of Physics*. [doi:10.1063/1.3518969]

I. INTRODUCTION

Plasma source ion implantation (psii), commonly referred to more recently as plasma immersion ion implantation (piii or pi^3), is an approach to carrying out ion implantation in which the substrate to be implanted is fully immersed in a plasma and repetitively pulse-biased to high negative voltage so as to accelerate ions from the surrounding high-voltage plasma sheath into the substrate surface.[1–5] The pulsed nature of the high voltage substrate biasing is essential: during the pulse-on phase energetic ion bombardment takes place and depletes the plasma for some distance around the substrate, and during the pulse-off phase the plasma is replenished. Since the substrate is immersed in the embedding plasma, while energetic ion bombardment (implantation) takes place during the pulse-on period, during the pulse-off part of the cycle plasma simply condenses on the substrate. For the case of a gaseous plasma this is of little concern, as the neutrals (plasma ions neutralized on the substrate surface) simply return to the vacuum as a gas. But in the case of a metal plasma the neutralized metal ions from the plasma remain on the substrate surface and a surface film slowly evolves. The film is subjected to energetic ion bombardment during the subsequent pulse-on time, and interface mixing occurs via knock-on collisions of the incoming energetic plasma ion with residual surface atoms remaining from the prior pulse-off plasma deposition phase. One can see that the plasma immersion process in the case of a metal (or carbon) plasma is rather different from the plasma immersion process in the case of a gaseous plasma. The acronym Mepiiid, for metal plasma immersion ion implantation and deposition, is widely used to refer to the process, and the technique and its applications have been described in the literature.[4–7]

The plasma immersion technique has a number of advantages over the more conventional "beam line implantation" process in which an ion source located some distance from the target produces an energetic ion beam that is used to bombard the implantation substrate. (There are also some disadvantages—there are tradeoffs both ways). Although quite simple in concept, the immersion process calls for a high voltage pulser with performance parameters ("specs") that can be challenging. Thus for example it is often the case that the peak pulse current must be in the ampere or tens-of-amperes range, which for pulse voltage (ion energy) in the tens-of-kV range implies peak pulse power in the hundreds of kilowatts or even megawatt range. Also it is generally advantageous and often even essential that the pulse risetime be not vastly longer than the inverse ion plasma frequency, $\omega_{pi}{}^{-1}$, usually meaning sub-microsecond risetime. In general the pulser is the major hurdle to setting up a plasma immersion system.

For the case of metal plasma immersion ion implantation and deposition, the demands on the pulser are yet more severe. If the vacuum arc source is a steady-state (nonpulsed) source, then the pulser must deliver its high power pulses on a steady (c.w.) basis. In addition, the duty cycle cannot be small, or else the process will be dominated by surface film deposition with the ion implantation playing only a minor and perhaps insignificant role. But then the average power both required for the pulser and delivered to the substrate (in the form of ion bombardment) is extremely high—well into the tens-of-kW range or more. For most conceivable applications this power level is not feasible on a number of different counts. Thus it is the case that much vacuum arc plasma work, particularly when in conjunction with a plasma immersion setup (Mepiiid), is carried out on a repetitively pulsed basis. The vacuum arc plasma gun might be operated in pulses ~1–10 ms long at a repetition rate ~1 pps (pulse per second); then the duty

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cycle is ~0.1–1%. In this case the HV piii pulses can be delivered in pulse-packets that match the arc pulse (or plasma pulse), and the mean power required of the pulser is reduced by the same factor, $\sim 10^2$–10^3. Thus the pulser need have a mean power rating that is more feasible, say a few kW. This is the approach taken here.

At the same time, the same pulser, operated in a "repetitive pulse packet mode" as just described, is still well compatible with a gaseous plasma also, as opposed to a metal plasma. For a gaseous plasma there is no surface film formation and it is of little concern whether the HV micropulses arrive equally spaced or in bursts (pulse packets), so long of course as the plasma has adequate time to recover between pulses.

Our pulser was designed for compatibility with the condensable plasma formed by a repetitively pulsed vacuum arc plasma gun (in fact, two such guns operated sequentially so as to allow two metal species to be intermixed or layered according to experimenter design) as well as with the noncondensable plasma formed by an alternative gaseous plasma source. The filtered vacuum arc plasma gun system has been described in some detail elsewhere.[8,9] In brief, in this kind of plasma facility metal (and carbon) plasma can be formed in pulses typically several milliseconds long (here 5 ms) with a repetition rate typically 1 pps. The high voltage pulser is also compatible with an alternative gaseous plasma source which operates in steady-state mode (nonpulsed). We use a small hollow-cathode plasma source as has been described.[10]

II. DESCRIPTION OF THE PULSER

The high voltage pulser is housed in a roll-around rack that is 1.3 m high and 0.6 m square (Fig. 1). Mains power input is three phase, 220 V at a maximum power consumption of 2 kW. The unit can be operated in low voltage mode or high voltage mode. In low voltage mode the negative output pulses can be varied from –10 V to –500 V in 10 V steps, and in high voltage mode from –500 V to –20 kV in steps of 500 V. Maximum peak pulse current is 20 A, and this maximum current holds over the entire 10 V to 20 kV voltage range. Pulse width is variable from 2 to 180 μs with risetime of less than 1 μs (as low as 0.7 μs, depending on the load) and repetition rate of 5–50 kHz. The pulses are delivered in pulse packets of width variable from 1 to 10 ms at a repetition rate of 0.5–10 pps. Maximum duty cycle of the micropulses within a macropulse is 90%. Arc suppression is built in, with an arc suppression time of less than 1 μs. The control panel is small and simple and uses an LCD display. The pulser parameters are summarized in Table I, and typical oscillograms of the pulse voltage and current are shown in Fig. 2. Fig. 2(a) is for the case when the load is a 700 Ω resistor. Fig. 2(b) is for a plasma load; the initial large current spike is the current from the ion matrix sheath,[4,5] a feature typical of all plasma immersion operation. Fig. 3 shows the 5 ms long pulse packet, for the case of a resistive load.

The low voltage part of the power supply is designed using a conventional resonant inverter approach. A basic design feature of the high voltage part of the pulser is a cellular approach as described by Akemoto *et al.*,[11] an approach that provides high voltage pulses without the use of high voltage active elements. A much-simplified schematic of the high voltage part of the system is shown in Fig. 4. The high voltage part contains a resonant inverter which is connected to a transformer having a single primary winding and 20 secondary windings. Isolation between windings of the transformer is up to 20 kV. Each of 20 identical cells is connected

FIG. 1. Photograph of the pulser.

TABLE I. Pulser parameters.

Parameter	Value	
Input power	220 V, 3-phase, <2 kW	
Max average pulse power out	1.5 kW	
	Low voltage mode	High voltage mode
Max pulse voltage (negative)	500 V (10 V steps)	20 kV (0.5 kV steps)
Max peak pulse current	20 A	
Pulse risetime	<1 μs	
Pulse duration	2–180 μs (steps of 1 μs)	
Pulse rep rate	5–50 kHz (steps of 1 kHz)	
Pulse packet duration	1–10 ms (steps of 1 ms)	
Pulse packet frequency	0.5–10 pps (steps of 0.1 pps)	
Duty factor within pulse packet	10–90%	
Arc suppression time	<1 μs	
Weight	170 kg	
Dimensions	1.3 × 0.6 × 0.6 m	

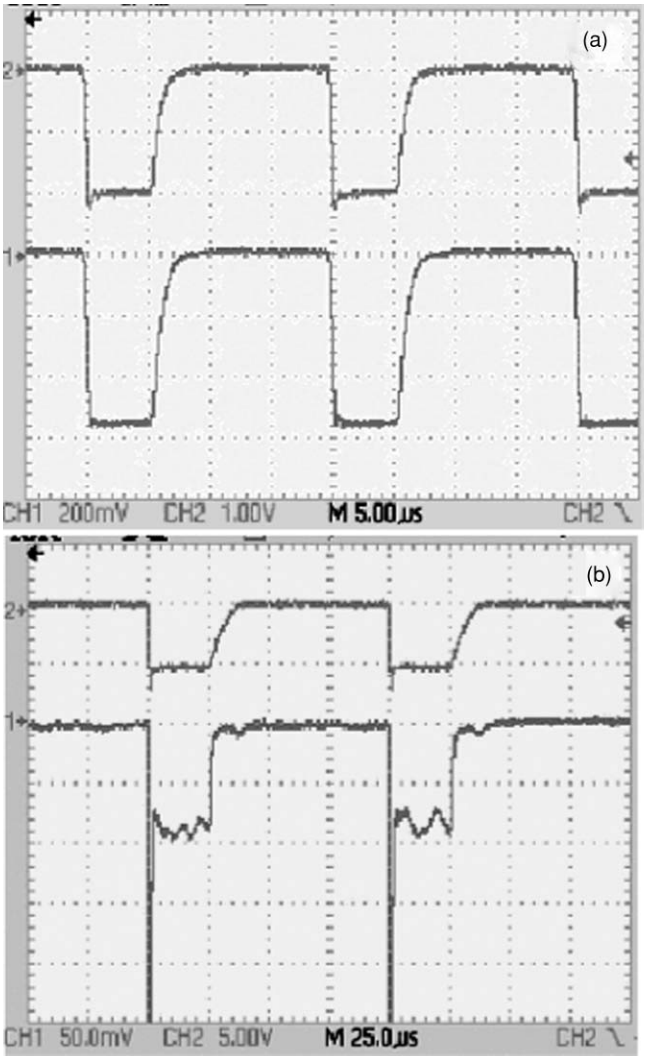

FIG. 2. Oscillograms of typical pulse voltage and current: (a) with a 700 Ω resistive load. Upper trace: voltage (1 kV/cm), lower trace: current (1 A/cm), sweep speed 5 μs/cm. Pulse width 5 μs, duty cycle 25% (pulse rep rate 50 kHz over the 5 ms macropulse); (b) with a plasma load. Upper trace: voltage (5 kV/cm), lower trace: current (250 mA/cm), sweep speed 25 μs/cm. Pulse width 25 μs, duty cycle 25% (pulse rep rate 10 kHz over the 5 ms macropulse).

to one of the secondary windings. Each cell contains a capacitor which is charged to 1 kV through a rectifier from one of the transformer windings, and an IGBT-switch switches this capacitor to the load. All cells are connected in series at the output. Switching of *n* cells thus generates a high voltage pulse at the load with amplitude *n* kV. Any number of cells may be switched. If a particular cell is not switched on, the output pulse current proceeds through a reverse diode in this cell. The 20 cells are controlled by a microcontroller via optical connections. The control board directs the operation of all cells, as well as providing feedback stabilization of pulse voltage and protection from arc overcurrent in the output.

This kind of cellular design of the high voltage pulser has a number of significant advantages over alternative approaches to high voltage pulse power generation. No high voltage pulse transformer is needed, in turn allowing the possibility of forming pulses of any duration and of short

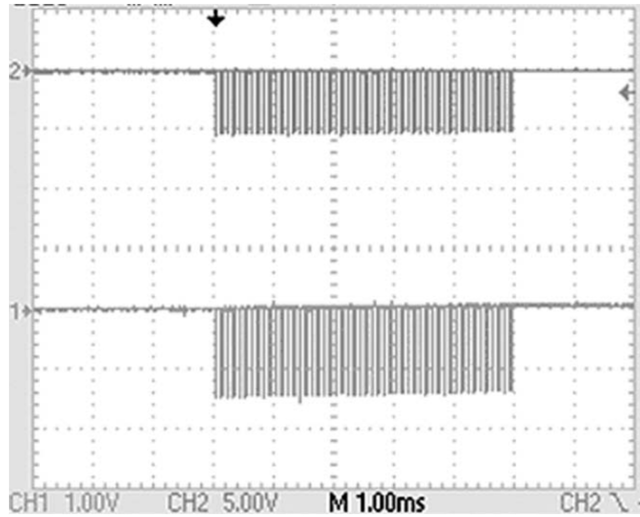

FIG. 3. Oscillogram showing the 5 ms long gated pulse packet. 700 Ω resistive load. Upper trace: voltage (1 kV/cm), lower trace: current (1 A/cm), sweep speed 1 ms/cm

rise-time. Further, there is no necessity for any high voltage or high current switches. The IGBTs and diodes used in the cells have operating parameters as called for by a single cell, (1 kV, 20 A), and therefore are of low cost.

III. INTERFACE MIXING FOR ENHANCED DLC THIN FILM ADHESION

Diamond-like carbon (DLC) thin films have attracted a great deal of research attention in recent years.[12–14] Among the various possible ways of forming these kinds of films that have been explored, the use of a filtered vacuum arc plasma deposition system, with carbon cathode so as to form a carbon plasma, is attractive in that the films are hydrogen-free whereas DLC films formed from a hydrocarbon precursor gas are heavily hydrogenated. Vacuum arc deposited DLC films are typically of high quality, meaning high sp^3:sp^2 ratio (ratio of diamond-bonded carbon atoms to graphite-bonded carbon

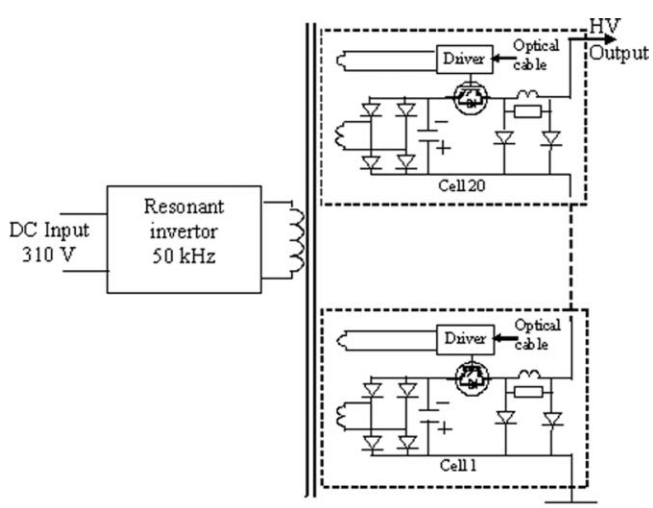

FIG. 4. Simplified schematic of the cellular high voltage approach adopted here.

atoms) and thus also have good tribological and other properties. The diamond-bonded fraction (sp^3-bonded fraction, or simply "diamond fraction") can be maximized at around 85–90% by biasing the substrate so that the C^+ ion deposition energy is approximately 100–200 eV.

It is a feature of DLC thin films that their inherent desirable tribological characteristics are unavoidably associated with high internal stress, and the higher the diamond fraction, the higher also the internal stress. This in turn leads to a tendency for the films to delaminate from the underlying substrate on which they are formed, a tendency which is accentuated with film thickness. Adherent, high quality DLC films are inherently limited to being quite thin, say <100 nm, and adherent thicker DLC films can be obtained only by reduction of the internal stress such as by lowering the diamond fraction.

On the other hand it is known that film adhesion can be enhanced by interface mixing—generating a gradual transition from substrate material to film material over some distance, perhaps some tens on nm, as opposed to a sharp interface between substrate and film materials. Interface mixing has been used widely to form thin films with superior substrate adhesion, including for the case of DLC films.[15] Here we choose this specific application simply as a demonstration of the operation of the plasma/pulser system. In the following we describe the use of our pulser, in conjunction with a filtered vacuum arc deposition system with carbon cathode, to demonstrate the formation of DLC films with superior substrate adhesion by virtue of interface mixing brought about by carbon plasma immersion ion implantation in the early stages of the film formation process.

We formed two, small DLC samples for comparison, one with interface mixing and the other without. The films were formed on small pieces (about 1 cm^2) of low-resistivity Si wafer, located some 7 cm distance from the exit of a quarter-torus bent-solenoid macroparticle filter through which the carbon plasma formed by a repetitively pulsed (5 ms pulses, 1 pps) vacuum arc plasma gun is passed. This setup has been described elsewhere.[8,9] Film thickness in each case was close to 200 Å, as determined by subsequent AFM profilometry. In order to maximize the diamond fraction in the DLC films the substrates were, in both cases, pulse biased to –100 V; thus the film internal stress was maximized and so also the tendency for delamination, which we wanted for this experiment. For the film without interface mixing, the vacuum arc plasma gun was pulsed for a total of about 2600 pulses; the –100 V substrate bias was achieved by using the pulser to form micropulses of width 5 μs and duty cycle 25% (50 kHz rep rate) within the 5 ms macropulses. For the film with interface mixing, we used the pulser first to provide –5 kV substrate bias micropulses for a total of about 380 macropulses; in this way an implanted layer of C (presumably in the form of SiC) was formed to a depth of about 300 Å.[16] Computer simulation using the TRI-DYN[17](Dynamic TRIM) program confirms the formation of an intermixed layer that is several hundred angstroms deep. Following this interface forming mode the pulser voltage was reduced to –100 V, without any pause in the deposition process. Thus the two samples were prepared identically except for the formation in one of a gradual transition in C atom fraction across the film/substrate interface.

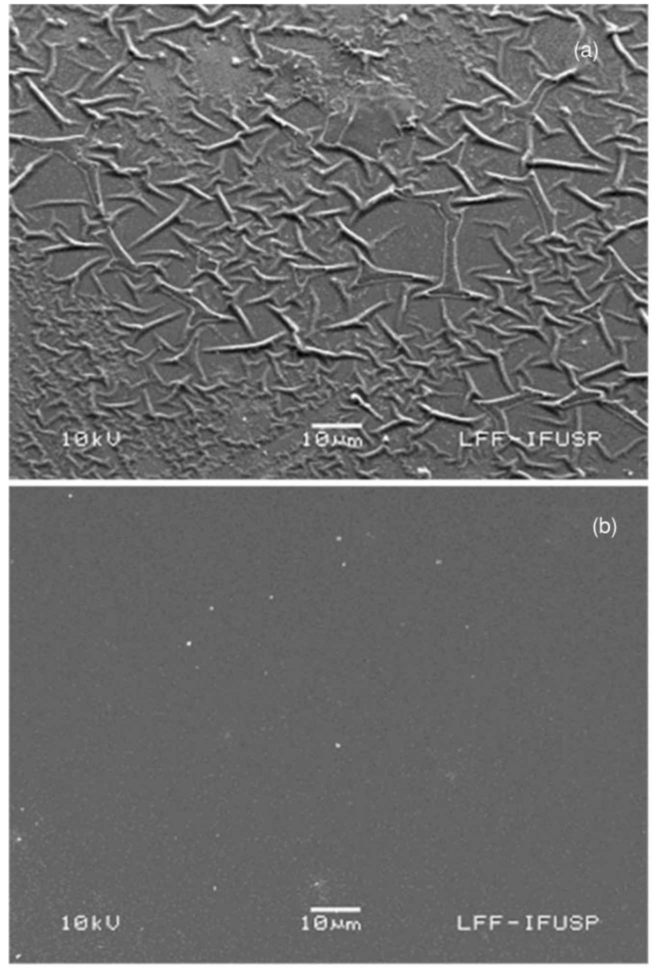

FIG. 5. SEM micrographs of DLC films formed with and without interface mixing: (a) no mixing; (b) with mixing as produced by 5 keV C^+ ion implantation prior to the DLC deposition. In both cases the DLC deposition was carried out with pulsed substrate bias of –100 V so as to maximize the sp^3-bonded carbon atom fraction in the film, and so also the film internal stress.

Scanning electron microscope (SEM) micrographs of selected regions of the two samples are shown in Fig. 5. Delamination of the noninterface-mixed DLC film is clearly visible, whereas the sample with interface-mixing shows no sign of delamination. Clearly the interface mixing provided by the pulser has resulted in enhanced film adhesion, as anticipated.

IV. CONCLUSION

We have described the design and operation of a high voltage pulser that operates in a gated pulse-packet mode such as is appropriate for operation with a repetitively pulsed vacuum arc plasma gun system in metal plasma immersion ion implantation and deposition (Mepiiid) configuration. The pulser design makes use of some novel features, and provides micropulses up to 20 kV at up to 20 A, within a gated macropulse of duration up to 10 ms. The application of the pulser was demonstrated by using it to carry out interface mixing at the film/substrate boundary for the case of a high quality (high sp^3 content, and thus also high internal stress) DLC thin film formed on a silicon substrate; film delamination was avoided for the case of an interface-mixed deposition process, compared to obvious delamination for a similar film without interface mixing.

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