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A self-sputtering ion source: A new approach to quiescent metal ion beams

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A new metal ion source is presented based on sustained self-sputtering plasma in a magnetron discharge. Metals exhibiting high self-sputtering yield like Cu, Ag, Zn, and Bi can be used in a high-power impulse magnetron sputtering (HIPIMS) discharge such that the plasma almost exclusively contains singly charged metal ions of the target material. The plasma and extracted ion beam are quiescent. The ion beams consist mostly of singly charged ions with a space-charge limited current density which reached about 10 mA/cm^2 at an extraction voltage of 45 kV and a first gap spacing of 12 mm.

I. INTRODUCTION

For some time, it is known that sputtering can be sustained with ions of a sputtered target ("self-sputtering") if such ions are generated at a sufficient rate.[1-3] For a very limited number of elements exhibiting very high sputter yield, the self-sputtering process can be obtained in direct current (DC) mode. A much larger number of elements can be used for sustained self-sputtering when the discharge voltage and related power is significantly enhanced beyond typical DC values: in theses cases one resorts to a pulsed mode to keep the average power reasonably low[4]. Pulsed self-sputtering is closely related to the recent developments of high power impulse magnetron sputtering (HIPIMS) which is used for metal ion etching as well as deposition of dense metal and compound films.[5]

Using mass/charge spectrometry, it has been established that target materials with high self-sputtering yield tend to be dominated by singly charged ions,[6] while those with low yield also contain doubly and higher charged ions.[7,8]

Self-sputtering metal plasma can be obtained without any gas provided the discharge is started without gas; this can be done, for example, using the metal plasma of a very short (~ 10 μs) vacuum arc.[9] However, it complicates the setup by needing an extra discharge circuit and arc cathode.

The main idea of a *self-sputtering ion source* is to utilize the dense plasma of the self-sputtering magnetron discharge and extract ions from it. This has been recently reported[10] and here we extend the information to situations using other metal and gas combinations. Some background gas is used to enable starting of the HIPIMS pulses without the need for an arc trigger plasma, although it is conceivable that, in principle, the approach presented here could also be done in high vacuum without any gas supply.

II. EXPERIMENTAL SETUP

The experimental setup was based on modifications to the "Mevva V" ion source facility at Lawrence Berkeley Lab.[11] The vacuum arc discharge unit was replaced by a 5 cm (2 inch) planar magnetron as indicated in Fig.1.

The extraction system was a simple, non-Pierce multi-aperture three-grid arrangement of the acceleration-deceleration type, where the accelerating grid distance was 12 mm and the diameter of each of the 163 holes was 4.7 mm. A fine mesh with 60% transmittance was spot-welded to the plasma-facing side of the first grid, resulting in a nominal extraction area of 17 cm^2. Using the Mevva facility had two advantages: first we could make use of the available high voltage power supplies, the time of flight (TOF) spectrometer, the magnetically Faraday cups, and other components. Second, a direct comparison with the conventional vacuum arc ion source, so far the most prolific metal ion source, is readily doable.

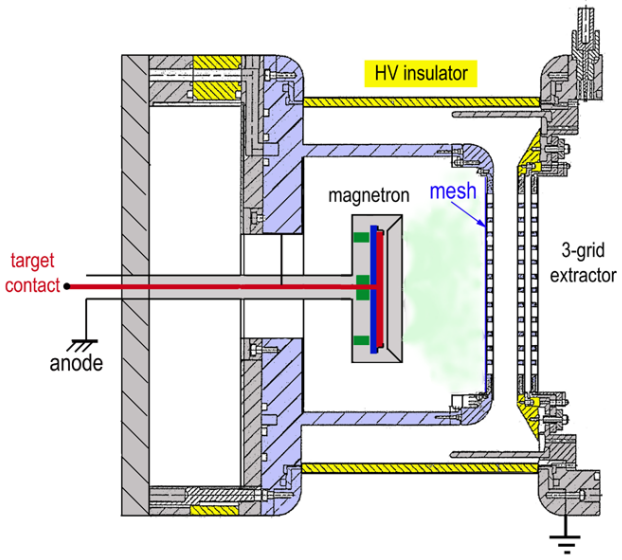

FIG. 1. (Color online). Experimental setup: a planar magnetron is used as the plasma generator in Berkeley Lab's 'Mevva V' ion source.

The pulsed magnetron discharge current was provided by a 3 Ω, 250 μs pulse-forming-network (PFN) charged up to 1000 V. The whole system operated at a potential of up to 45 kV above ground to allow extraction of ions from the self-sputtering plasma. The grids were also used to limit gas flow conductance between the discharge zone and the main chamber, the latter being pumped by a 1500 l/s cryogenic pump. In this way it was ensured that a sufficiently initial gas pressure (~ 0.2 Pa) and later high plasma density can exist near the target while the mean free path in the time-of-flight spectrometer is larger than the spectrometer's length. We operated in a narrow window of gas pressure: it was just high enough to get the magnetron started

upon application of the discharge voltage. To assist with ignition and stable pulse operation, the plasma expansion chamber, i.e. zone between magnetron target and first extraction grid, was kept at the negative target potential. In this way, the pre-target chamber served as a hollow cathode, confining plasma electrons, and thereby assisting ionization. For more details we refer to our previous publications.[6,10]

III. EXPERIMENTAL RESULTS AND DISCUSSSION

In agreement with previous findings, target materials of high self-sputtering yield (such as Cu, Ag, Bi, Zn) switch readily from gas-dominated sputtering to self-sputtering if the discharge power is high and the discharge duration is long enough that ionization and return of the ions to the target can occur. For our 5 cm planar target, typical currents are 10s of A with a minimum discharge duration of ~ 100 μs to be in sustained self-sputtering mode.

For a certain range of current and voltage, and high sputtering yield target materials, the self-sputtering mode is associated with quiescent (low-noise) plasma: voltage, current, and ion collector currents exhibit low noise. Although gas is used to initiate the discharge pulse, it is quickly replaced by sputtered metal and the TOF spectrometer shows mostly singly charged ions and very little gas ions. Figs. 2 and 3 show examples of high yield target materials and gas, and other metal-gas combination are similar. The percentages of doubly and higher charged ions are very small, and in some cases less than the TOF detection limit, i.e. less than < 1% of the plasma.

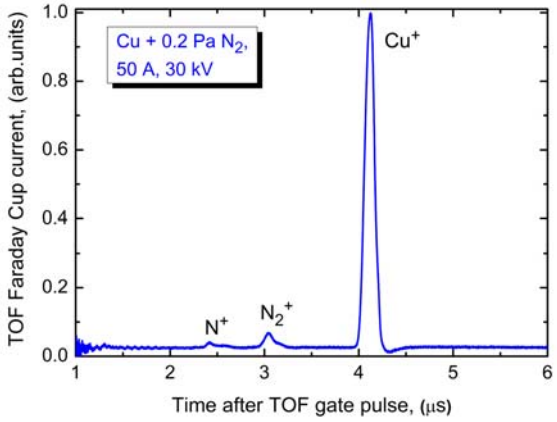

FIG. 2. (Color online). Time-of-flight spectrum of the ion beam for a copper target with nitrogen gas (0.2 Pa), measured 100 μs after the current pulse started. Discharge current 50 A, accelerating voltage 30 kV.

Overall, the properties of the target material are more important than the properties of the gas. This is evident when considering target materials of lower sputtering yield, for which it is not possible to reach the "pure" sustained self-sputtering mode within the voltage limits of the PFN power supply. For such metals, a large fraction of gas remains in the plasma, and the metal shows a significant fraction of doubly charged ions.

Returning to high yield materials, the speed of gas replacement is fast (~ 50 μs) and the plasma composition remains stable throughout the pulse (Fig. 4). One can see that despite the presence of background gas, the metal content of the ion beam can exceed 90%. It is conceivable that (a) pure metal beams can be obtained if the gas-ignition approach was replaced by a pulsed vacuum arc approach, as demonstrated in ref.[9], and (b) a continuously operating ion source could be made if the issue of heat management can be resolved.

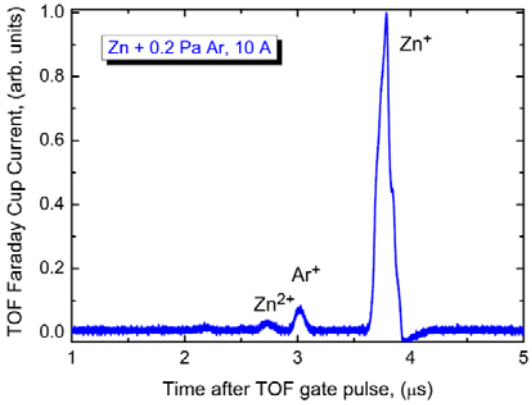

FIG. 3. (Color online). Time-of-flight spectrum of ion beam for zinc target with argon (0.2 Pa), measured 200 μs after the current pulse started. Discharge current 10 A, accelerating voltage 30 kV.

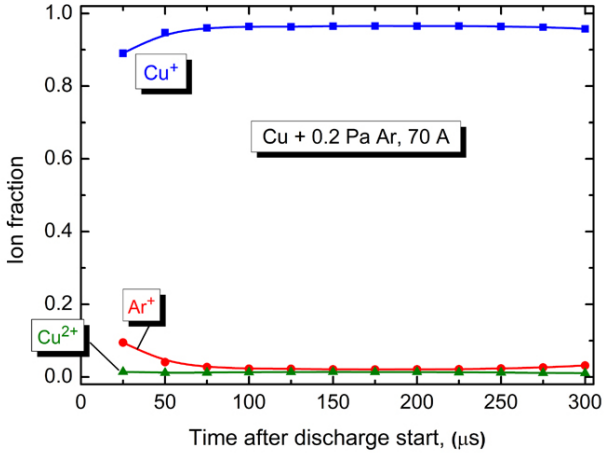

FIG. 4. (Color online). Temporal development of ion beam composition for copper target with argon (0.2 Pa); discharge current 70 A, accelerating voltage 30 kV.

There are a number of interesting details that can be compared when making ion beams from vacuum arc plasmas and HIPIMS self-sputtering plasmas. From energy considerations, it is reasonable to assume that the discharge power determines the production of an adequate plasma density. Experimentally, the arc current needed to obtain a comparable beam is much higher for the arc (~200 A) than for the HIPIMS case (~50 A), though the arc voltage is much lower (~25 V) than the HIPIMS voltage (~800 V). Multiplication of those numbers gives the power during the pulse: about 10 kW for the arc versus 40 kW for the HIPIMS discharge. Looking at the area density where most of this power is dissipated, we find the very small area of cathode spots (typically some 1-10 μm^2) versus the active racetrack area on the target, which is about 5 cm^2 in our case. We see that the power density for the arc is much greater, which explains the presence of multiple charge states for the vacuum arc case. In the HIPIMS plasma, we can assume that less doubly charged ions are produced in the first place, and if they are produced they may become singly charged via non-resonant charge exchange

collisions with the many neutrals that are produced by sputtering.

The emission of neutrals from the 'racetrack' zone of the target occurs with a wide angular spread, and as a result, the presence of the 'racetrack' zone becomes increasingly fuzzy as we consider the plasma away from the target. Measurements of the ion beam with a movable Faraday cup, which was equipped with magnetic suppression of secondary electrons, indicated that the 'racetrack' profile of the plasma generation is smeared out by the time the sputtering plasma is in contact with the first extraction grid, hence the beam is broad and radially uniform over several centimeters from the beam axis. The current density determined with the Faraday cup is typically 10 mA/cm^2 for an electric field of 37.5 kV/cm (45 kV across 12 mm). Fig. 5 gives a more specific example for the case of copper plasma (here, nitrogen gas was used for ignition of the pulses). The total ion current extracted is clearly a function of the extraction voltage, indicating space charge limitation. The curves do not follow the ideal Child-Langmuir law because the extraction system was not optimized in terms of ion optics.

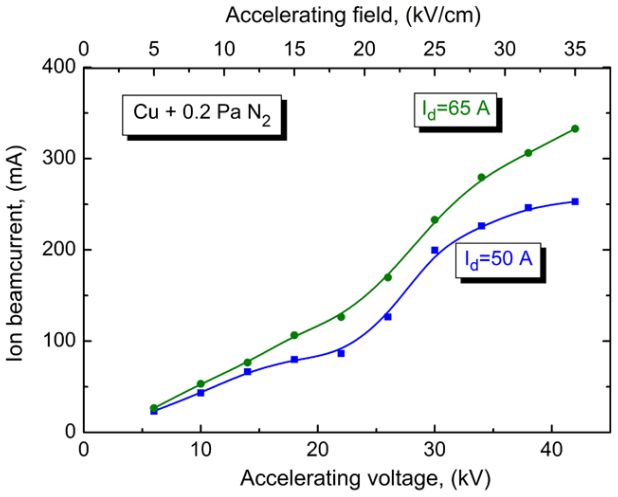

FIG. 5. (Color online). Total ion beam current vs. accelerating voltage, at a gap spacing of 12 mm, for Cu target with 0.2 Pa N_2.

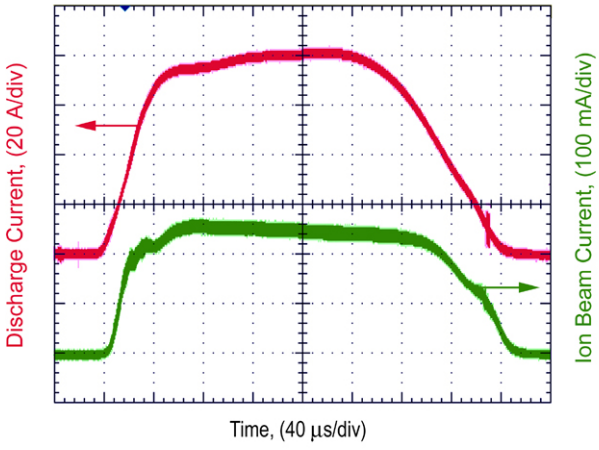

FIG. 6. (Color online). Discharge current (upper trace, 20 A/div) and ion beam current (lower trace, 100 mA/div) in "envelope" mode for 20 pulses; Cu target with 0.2 Pa argon.

Finally, we illustrate the quiescence and remarkable reproducibility of the beam by using the envelope mode of the oscilloscope to show cumulative pulse-to-pulse deviation (Fig. 6).

The low-noise performance of a self-sputtering ion source is very different compared to a vacuum arc ion source because the vacuum arc plasma is produced at non-stationary cathodic arc spots, whereas the sputtering plasma does not show large amplitude fluctuations, at least for high yield materials and within certain power limitations. Preliminary experiments with low yield target materials, such as Ti and Nb, showed that higher voltage is needed to push the yields to high values. This resulted in larger amounts of multiply charged ions and promoted discharge instabilities.

IV. SUMMARY AND CONCLUSIONS

In the present contribution, further details are presented beyond our previous report[10] on a self-sputtering ion source. A magnetron was mounted as the plasma generator in the "Mevva V" ion source, replacing the vacuum arc discharge. For high yield sputtering materials, the plasma is dominated by singly charged metal ions with very small 'contamination' of doubly charged ions and gas ions. In contrast to the vacuum arc case, the ion beam extracted from the self-sputtering plasma is exceptionally reproducible and of low noise. By using larger targets and due to spatial broadening of the plasma beyond the magnetron 'racetrack', scaling to larger cross section seems to be straight forward. The limitations of the new ion source are mainly in the choice of target materials: low sputtering yield materials do not go readily in the self-sputtering mode, which leads to a larger fraction of gas ions, multiply charged ions, and plasma instabilities.

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