High power impulse plasmas for thin film deposition

Fortgeschrittenen-Praktikum

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23 March, 2012

The Electrostatic Quadrupole Plasma (EQP) Mass Spectrometer is an experimental instrument used to measure the ion energy distribution function of atoms and ions in the plasma and to perform the mass analysis of the plasma. In this practical course the student will investigate the ion energy distribution function (IEDF) of metal and Ar atoms in High power impulse magnetron sputtering (HIPIMS) plasma discharge.

Students should already pass introduction in the plasma physics 1

Table of Contents

1. Theory

1.1 Magnetron sputtering

Gas discharges can be initiated when the voltage across the electrode is equal to or exceeds the static breakdown voltage gap V. Increase in voltage results in an abrupt increase in current, which is accompanied with an increase in glow intensity in the gap. DC glow discharges have long been used as sputtering sources for metallic materials. Figure 1 a) illustrates planar DC glow discharge driven by a constant current dc source [1]. The upper electrode, which is a cathode, serves as the target for ion impact sputtering. The substrate, on which the sputtered atoms are deposited, is placed on the lower electrode which is the anode.
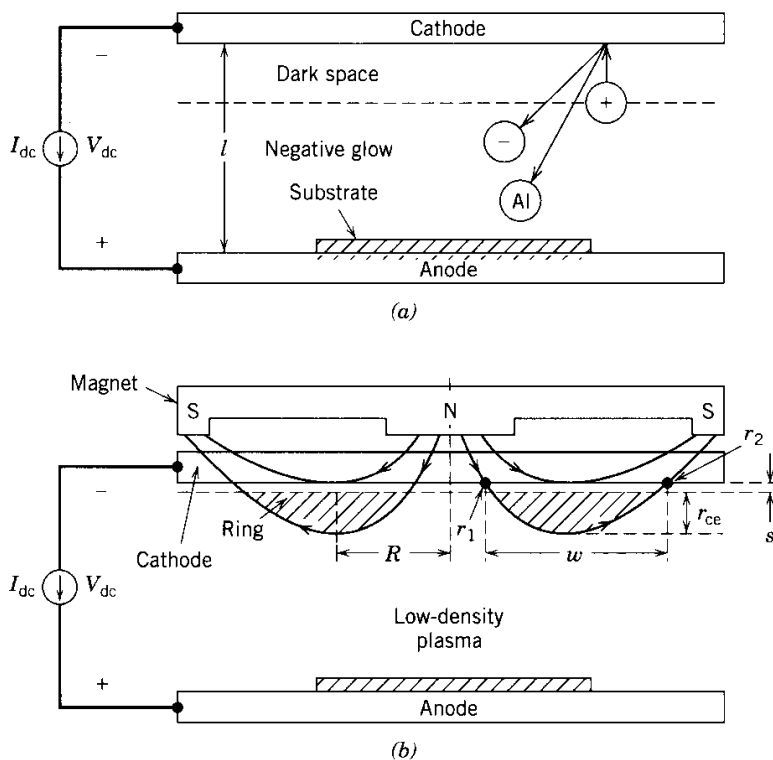
Figure 1 Schematic of a) DC glow discharge and b) DC magnetron discharge adapted from [1].

The discharge is maintained by secondary electron emission from the cathode, with the energetic secondary electrons providing the ionization required to maintain the discharge. However, operating pressures must be high enough, p > 4 Pa (30 mTorr), so that secondary electrons are not lost to the anode or side walls. This pressure is higher than optimum for deposition of sputtered atoms onto the substrate due to scattering of sputtered atoms. The drawback of the DC glow discharge is the low sputtering power efficiency, which is decreasing with increasing energy. It is necessary to operate

a sputtering discharge at higher densities, lower voltages and lower pressures. In order to confine the secondary electrons permanent magnets were placed behind the cathode to create the closed magnetic field lines where the electrons would be trapped. An axisymmetric dc magnetron discharge configuration is shown on Figure 1 b). A discharge is formed when a negative voltage of 200 V or more is applied to the cathode. Plasma in the magnetron discharge will be seen as the bright circular plasma ring of width w and mean radius R. The sputtering will occur in a track below the plasma and the area with eroded sputter profile is called racetrack. The plasma shields the electric field through most of the chamber and a cathode sheath s of the order of several Debye lengths develops, which sustains most of the externally applied voltage. Due to the high mass, magnetic field doesn't confine working gas ions in the plasma which are accelerated toward the cathode and strike it at high energy. In addition to sputtering material, the impact of the ions produces secondary electron emission. These electrons are accelerated back to the plasma and are confined near the cathode by the magnetic field. The electrons undergo a sufficient number of ionizing collisions to maintain the discharge before being lost to a grounded surface [2, 3].

Both electric and magnetic field are present in a magnetron discharge. The electric field accelerates electrons away from the cathode and ions towards the cathode. Magnetic field has a circular shape from the edge towards the centre of the cathode. The Larmor orbit of electrons is small compared to curvature of the magnetic field, thus electrons follow magnetic lines and are being entrapped in the magnetic field. This enables longer path lengths of electrons and increases the number of ionisation collisions. The magnetic field lines of the magnetron could be set up as completely closed, known as balanced magnetron (Figure 2 a)), or closed in the middle and open at the edge of the magnetron, called unbalanced magnetron (Figure 2 b)). Balanced magnetrons have magnetically trapped electrons and low ion flux to the substrate, which is advantageous for deposition of thin films on polymer substrates since it cannot withstand high ion flux density created in the unbalanced magnetron. In the unbalanced magnetron ion flux to the substrate is increased as well as ionisation of metal atoms in vicinity of the substrate. Unbalanced magnetrons are advantageous for hard coatings [2].
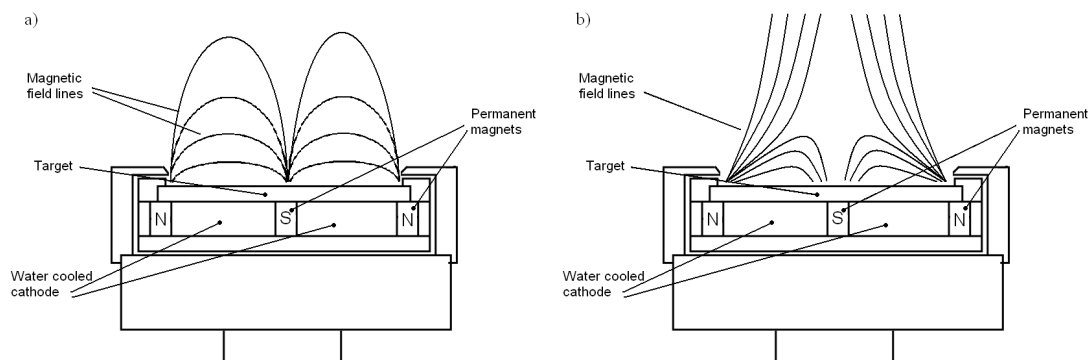

Figure 2 Schematic of the a) balanced magnetron, with closed magnetic field lines and b) unbalanced magnetron with magnetic field lines open at the edge of the target, from [1]

1.2 Direct current (DC) magnetron sputtering

Direct current (DC) magnetron sputtering is a sputtering technique that uses magnetic fields to enhance and confine the plasma, mainly electrons in the target vicinity. In a conventional DC plasma discharge, the cathode is kept at a constant negative voltage. Positive ions generated in the plasma are accelerated towards the cathode, sputtering atoms and molecules from the target surface. Secondary electrons are emitted and accelerated away from the target surface as a result of the ion bombardment. Secondary electrons are confined in the magnetic field near the cathode. Metal from the target is sputtered by ion bombardment and ionised by electron impact ionisation. DC magnetron sputtering is a line-of-sight process, since it generates mostly neutral atoms whose trajectory and energy cannot be easily controlled, therefore rather low pressures are used to minimize scattering of the sputtered atoms [1]. Diffusion of the electrons and ions in the DC magnetron sputtering through the chamber, shown on Figure 3, shows similar spatial density distribution of electrons and ions that supports the theory of plasma quasi-neutrality.
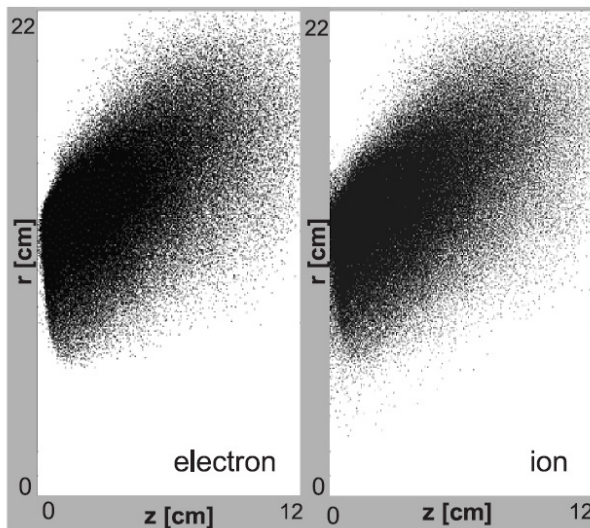

Figure 3 Simulated electron and ion distribution in the space near the target

1.3 Influence of adatom mobility on the film density

DC magnetron sputtering improved deposition rate and quality of the coating compared to glow discharge. However the simulations done by Muller [8] showed importance of the adatom energy on the microstructure of deposited coating. He investigated adatom migration effects using microstructure evolution growth simulation. Muller found that above a critical temperature range the porous columnar microstructure changes to a configuration of maximum packing density, Figure 4. Film deposited at 350 K shows columnar structure. Increasing deposition temperature from 350 K to 420 K, film densifies but columnar structure is still visible. Increasing deposition temperature to 450 K fully dense film is deposited with local defects. Apart from heating the substrate energy can be

conveyed by energetic ions impinging onto the substrate. Using negative bias on the substrate energy of impinging ions can be controlled. Disadvantage of DC magnetron sputtering is low ionisation of sputtered metal. Therefore metal particles arriving to the substrate comprise mainly neutrals that are not affected by substrate bias. The ionisation of sputtered metal can be increased by increasing the discharge power, however thermal load onto the target get increased that can lead to melting of the target.
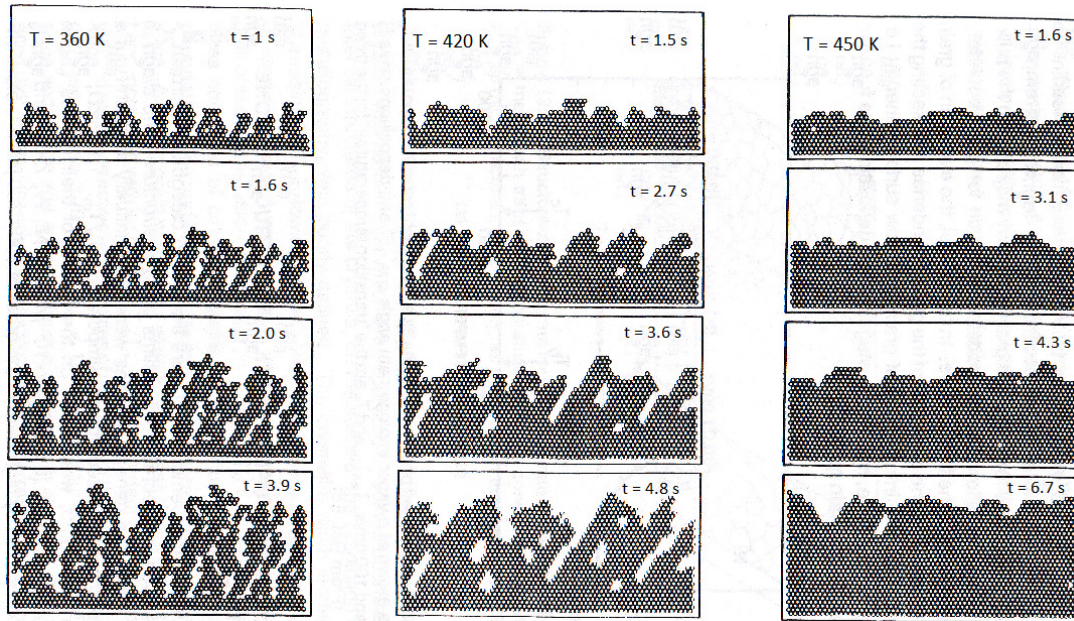

Figure 4 Two dimensional microstructure simulation of Ni films deposited as a function of temperature, from [61]

1.4 High power impulse magnetron sputtering (HIPIMS)

In 1999 a method was suggested where high power is delivered to the target in short pulses $\sim$ 100 μs with repetition frequency of $\sim$ 100 Hz and duty cycle of $\sim$ 1%. By pulsing the target voltage a lot of power is delivered to the target that generates high ionisation of sputtered metal portion, and low duty cycle imply average powers being comparable to the DC powers without increasing thermal loads on the target.

The main advantage of HIPIMS over DC magnetron sputtering is increased ion to neutral metal ratio. Increase in the ion to neutral ratio of Cr (triangles and circles) and increase in the ion current density and deposition rate (squares) with increase of target current, Figure 5. At peak target currents of around 25 A, ration of Cr^+ and Cr^0 is 1 indicating 50% ionisation of sputtered material. The increase in the ion to neutral ratio is the consequence of increased electron density in the target vicinity. On Figure 6 linear dependence of the electron density on the peak discharge current is shown. The time and spatial evolution of the electron density was measured revealing electron densities above 10^{19} m^{-3}. The results presented on Figure 7 show electron densities above 10^{18} m^{-3} in the chamber even at 640 μs from the start of the pulse.
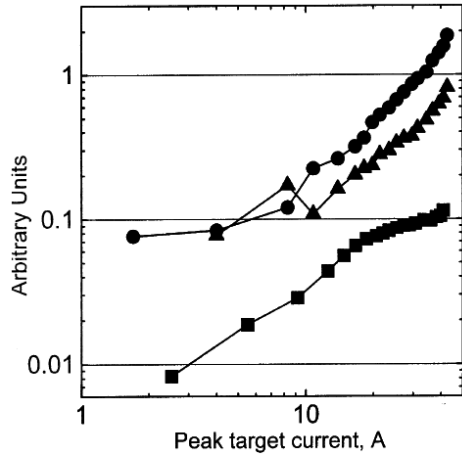
Figure 5 Ion to neutral ratio and deposition rate as a function of target current. Triangles represent $I(Cr^{2+})/(Cr^0)$, circles represent $I(Cr^+)/(Cr^0)$ and squares represent the ratio of ion current density to deposition rate
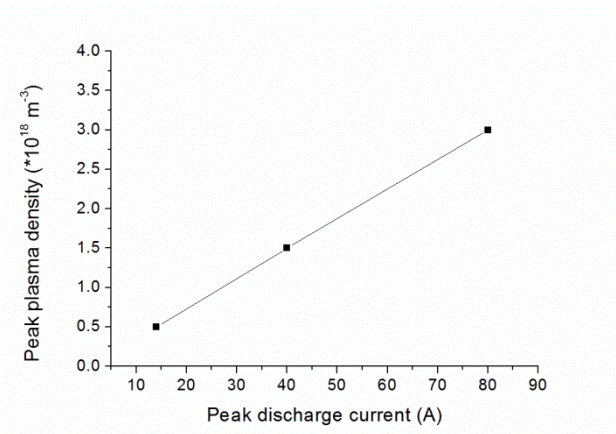

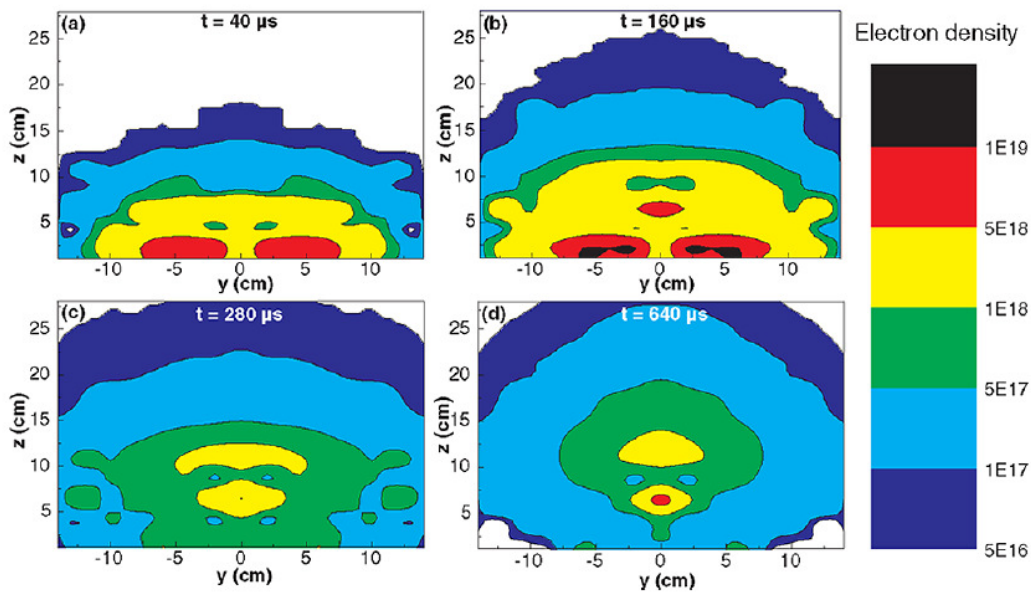Figure 6 Plasma density as a function of peak discharge current in the HIPIMS discharge

Figure 7 Temporal and spatial variation in the electron density below the target at 40, 160, 280, and 640 µs after pulse ignition

High powers in the pulse result in amplified sputtering of the target. Increased density of sputtered material in the target vicinity and momentum transfer from sputtered particles to Ar particles leads to effect called Ar rarefaction. The effect of Ar rarefaction is presented on Figure 8. The results show substantial Ar rarefaction with gas density reduced tenfold in the close vicinity of the target.
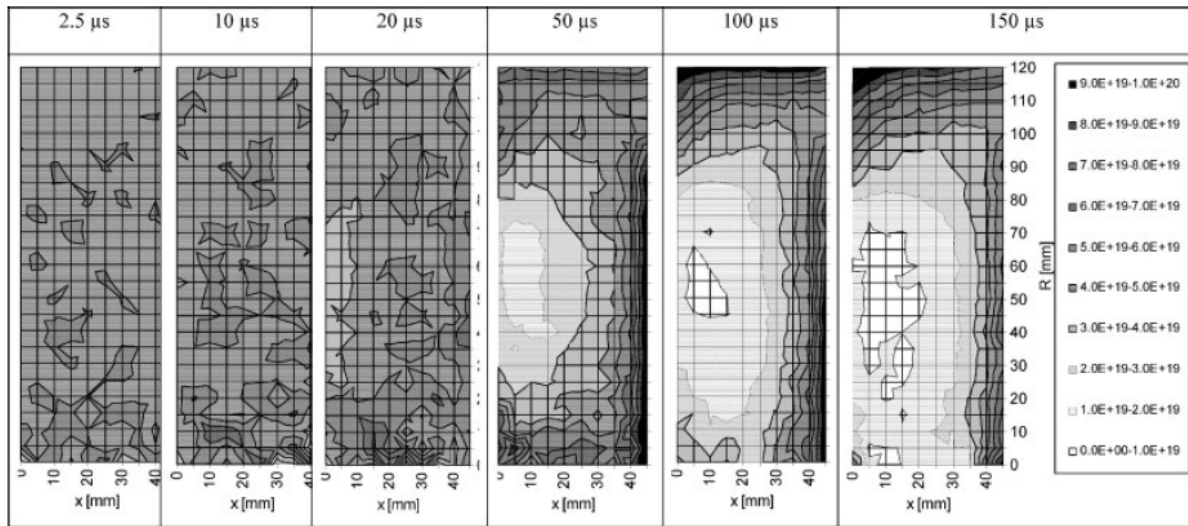

Figure 8 Time evolution of Ar gas density of in m^{-3}. On the left side is the target, x is the distance from the target and time on the top of the image represents time within the discahrge

The IEDF of metal and Ar ions in HIPIMS obtained using plasma sampling mass spectrometry showed that, during the pulse, a Thompson-like high energy tail distribution of metal IEDF with energies up to 100 eV has been reported. Whereas after the pulse metal ion IEDF comprised of a main low energy peak and a high energy tail, for measurements recorded in the vicinity of the target. Time resolved measurements comparing the rise of the discharge current to the end of the pulse have shown the existence of a single low energy peak in the post discharge. Several papers used mass spectrometry to describe the influence of pressure on the IEDF and the influence of power on the IEDF. Increasing the working gas pressure the high energy tail of the metal IEDF was reduced and the low energy peak of the metal IEDF increased and narrowed as a result of thermalisation.

The OES measurements of HIPIMS of Cr showed that, in the beginning of the pulse, the plasma is dominated by Ar^{0} atoms and Ar^{1+} ions. At the peak of the discharge current Cr atoms and Cr^{1+} and Cr^{2+} ion signals appear. The intensity of the Ar species signal drops with the discharge current and the Cr^{1+} signal dominates the end of the pulse. After the end of the pulse, the Cr^{1+} signal drops and the Cr^{0} signal is dominant.

The ion saturation current measured at different distances from the target showed that ions are able to leave the magnetized region and reach the substrate in greater numbers depending on the peak current, which is the consequence of the kinetic pressure exceeding the magnetic pressure.

1.5 Plasma sampling mass spectrometer

The mass and relative concentrations of atoms, ions and molecules and their energy distribution is measured using plasma sampling mass spectrometer. Schematic picture of plasma sampling energy resolved mass spectrometer showing main parts is shown on Figure 9.
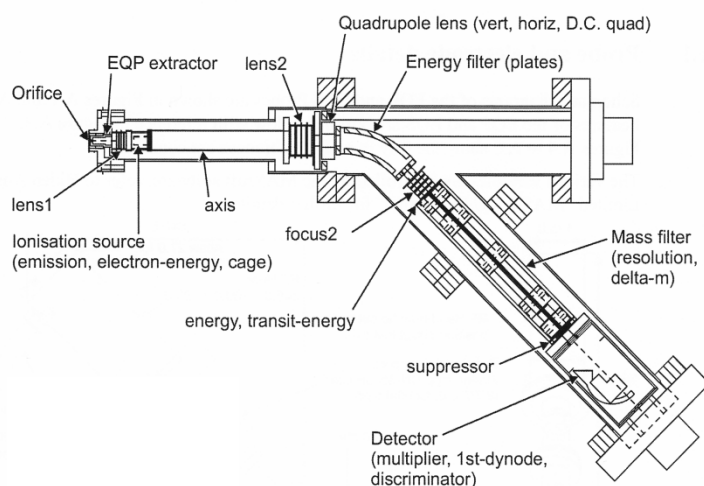

Figure 9 Schematic of the mass spectrometer [5]

The ions are extracted from the plasma and focused by applying direct current voltage on the extractor electrode and by the lens electrode. Voltages on the extractor electrode and on the lens electrode are around -10 V and -79 V, respectively. Negative voltage on the extractor is used to repel electrons and accelerate ions. In the next step it is possible to choose Residual Gas Analysis (RGA) mode that uses internal impact ionisation source for ionisation of neutrals from the plasma. In this practice RGA mode was not used since only ions generated in the plasma were analysed. The ions from the extraction electrodes are then filtered by the energy filter. Remaining ions are further filtered by their mass-to-charge ratio in the quadrupole mass analyzer (QMA). Ions with the selected mass-to-charge ratio are detected in the detector. The secondary electron multiplier (SEM) is used as an ion detector. A secondary electron multiplier consists of a series of electrodes called dynodes, each connected along a string of resistors. One signal output end of the resistor string is attached to the positive high voltage and the other end of the string is grounded. The dynodes maintained at increasing potential create a series of amplifications. When a particle, e.g. ion, strikes the first dynode it generates secondary electrons. The secondary electrons are then accelerated into the next dynode where each electron produces more secondary electrons, thus generating a cascade of secondary electrons. Typical amplification is of order 10^6 generated electrons per one incoming particle [6, 7].

Mass analyzer separates the ions according to their mass-to-charge ratio. All mass spectrometers are based on the dynamics of charged particles in electric and magnetic fields in the vacuum where the Lorentz law:

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B} \qquad (1)$$

and Newton second law applies:

$$\vec{F} = m\vec{a} \qquad (2)$$

where $\vec{F}$ is the force applied to the ion, q is the ion charge, $\vec{E}$ is the electric field, $\vec{v} \times \vec{B}$ is the vector cross product of the ion velocity and the magnetic field, m is the mass of the ion and $\vec{a}$ is the acceleration. Equating the eq. (1) and eq. (2) the expressions for the force applied to the ion yields;

$$\frac{m}{q}\vec{a} = \vec{E} + \vec{v} \times \vec{B} \qquad (3)$$

where m/q is called mass-to-charge ratio. Initial conditions of the particle and equation (3) are completely determining the particle motion in space and time. Two particles with the same mass-to-charge ratio (m/q) behave the same. This is the basic principle of mass spectrometry.

The quadrupole mass analyzer (QMA) (Figure 10) consists of four parallel metal rods. Each opposing rod pair is connected together and a radio frequency (R.F.) voltage is applied between one pair of rods, and the other. A direct current voltage is then superimposed on the R.F. voltage. Ions travel between the rods and through the quadrupole. Only ions of a certain mass-to-charge ratio will reach the detector for a given voltage parameters. Other ions will be lost due to collisions with rods and the wall of QMA. This allows selection of a particular ion, or scanning by varying the voltages.
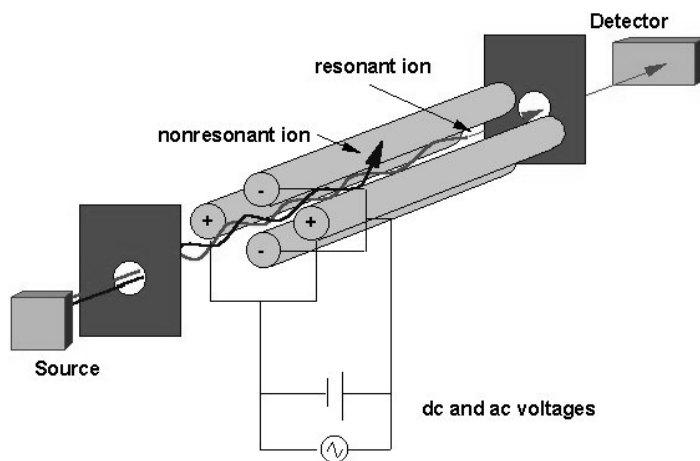

Figure 10 Schematic of the quadrupole mass analyzer showing resonant ion passing the analyzer and reaching the detector and nonresonant ion scattered in the analyzer

In this practice the plasma mass spectrometer was used for two purposes. First was measuring mass spectrum of the plasma. Second was measurement of the ion energy distribution. An example of a mass spectrum of a HIPIMS of Cr discharge is shown in Figure 11.
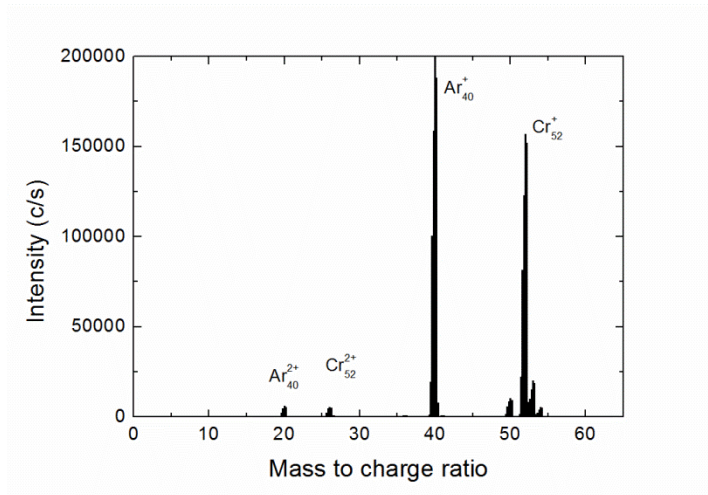
Figure 11 Mass spectrum of HIPIMS plasma discharge for Cr target in Ar atmosphere taken at an ion energy of E = 0.5 eV at pressure of p = 0.29 Pa

Mass spectrum is measured by setting a fixed voltage on the Bessel box to define the ion energy and changing the voltage on the QMA, therefore scanning through the mass-to-charge ratio. On Figure 11 it is possible to recognize main isotopes of chromium, Cr^+ at m/q = 52 and Argon, Ar^+ at m/q = 40. The unified mass unit of Cr isotope is 52 and once ionized Cr ion has q = +1, thus mass-to-charge ratio, m/q for Cr^+ is equal to 52. On Figure 11, one can recognize stable Chromium isotopes Cr_{53} (m/q = 53) and Cr_{54} (m/q = 54) and long life isotope Cr_{50} (m/q = 50) with half-life of 1.8 e+17 y [30]. Twice ionized ions have q = +2, thus Cr^{2+} has m/q = 26 and Ar^{2+} has m/q = 20. On Figure 11 peaks for Cr^{2+} with m/q = 26 and Ar^{2+}, with m/q = 20 can be seen.
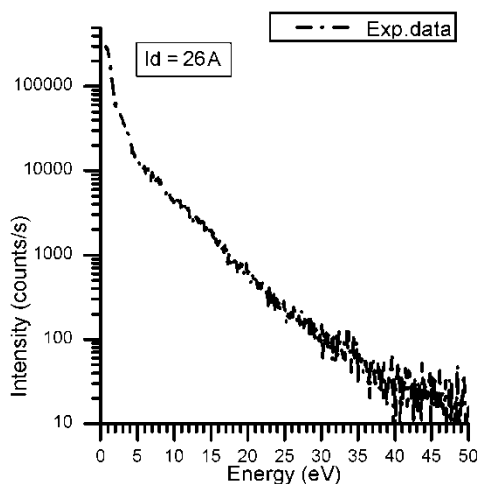

Figure 12 Ion energy distribution function for Cr^+ in Ar atmosphere at pressure p = 0.29 Pa

The energy distribution of Cr^+ ion is measured by setting QMA to enable only ions with m/q = 52 and then scanning all energies using the energy filter. Figure 12 shows an example of the Cr^+ ion energy distribution in Ar atmosphere at pressure of 0.29 Pa.

11

The initial IEDF for Ar ions differ from metal ion energy distribution. Before the pulse Ar particles are in thermal equilibrium (thermalised) at room temperature at 300K. Maxwell distribution describes the energy spectrum of particles in thermal equilibrium, $F_M(E) = 2\sqrt{\frac{E}{\pi(k_B T)^3}}\,exp\left(\frac{-E}{k_B T}\right)$, where E is the energy of the particle, k_B is Boltzmann constant and T is the temperature of the system.

Distribution of metal particles sputtered from the target is Thompson distribution. Thompson distribution describes the energy spectrum of ejected atoms during sputtering process, $F_T(E) = 2\left(1 + \frac{E_b}{\Lambda E_{it}}\right)\frac{E_b E}{(E_b + E)^3}$, where E is energy of the ejected particle, E_b is surface binding energy of the target material, E_{it} is maximum recoil energy, and $\Lambda = \frac{4 M_i M_a}{(M_i + M_a)^2}$, with M_i and M_a are the masses of the incident atom and the sputtered atom.

Metal atoms are ionized through electron impact ionisation. Diffusing from the target metal ion collides among themselves and with Ar ions and atoms resulting in the thermalisation of metal ions.

The energy scale measured by mass spectrometry is represented in volts. To change the energy scale to eV it is necessary to multiply it by the charge of the particle, e.g. in case of doubly charged ions the energy scale should be multiplied by two to obtain the energy scale in eV.

1.5.1 Time averaged mode

Mass spectrometer acquires data at certain energy for a specified length of time. Changing the acquisition time it is possible to measure the IEDF in time averaged and time resolved mode. In the time averaged mode the acquisition time is in order of several hundred milliseconds meaning the detector was collecting the ions arriving to the detector for 300 ms which is at frequency of 20 Hz around 6 pulses. The amount of ions detected at certain energy represents the number of ions detected both during and between the pulses. The IEDF measured in the time averaged mode gives information of ions arriving to the substrate during deposition.

1.5.2 Time resolved mode

In the time resolved mode the acquisition time is set to 20 µs and the detector was triggered from the power supply trigger. From the orifice of the mass spectrometer till the detector the ions need to go through the different parts of the mass spectrometer and the required time is called a time of flight, TOF_{ms}. The TOF_{ms} through the spectrometer is determined by the velocity of ions through its separate sections which are characterised by different accelerating or decelerating voltages. Calculator for the TOF for various species is given in excel file Transit.xls.

2. Instrument manuals

2.1 HIPIMS power supply

2.1.1 Setting the apparatus

Following apparatus should be running in order to run the HIPMS discharge

- Gas flow
  - o Switch on the MKS PR 4000
  - o Check that the both vents on the gas bottle are open
  - o Adjust the flow
  - o Switch the flow on and check the pressure on MKS PR 4000 mounted in the Vacuum pumps control rack
- Power supply
  - o Switch the power supply rack (Pulse unit is automatically switched on)
  - o Switch the DC unit
- Monitoring system
  - o Switch the current probe on
  - o Switch the oscilloscope on
  - o Check the voltage probe is connected on the back of the power cable plug
  - o Switch the magnetron cooling on

2.1.2 Setting the parameters

Huttinger TruPlasma Highpulse 4002 is the power supply used to generate the HIPIMS plasma discharge. Power supply is operated manually over the display located on the DC unit. In order to ignite the plasma several parameters must be set. These parameters are;

- Voltage
- Frequency
- Pulse duration
- Max charge

Parameters of the HIPIMS discharge are set using control panel mounted on the DC unit.

- On the control panel menus are changed by menu button to either
  - o Voltage menu (**Uout**) or
  - o Power menu (**POWER OFF**)

- Voltage menu
    - o In voltage menu scroll down to **ACCESS CODE** and change from **0** (STRD) to **1** (SETP)
        - ▪ In SETP mode two more menus are available but are not used (USER SETUP MENU and HUETTINGER menu)
    - o Scroll up and adjust the voltage
- Power menu
    - o Change pulse frequency at **PLS FREQ = 2x 25 Hz** (that is 50 Hz and only number 25 can be changed, max. 500 Hz)
    - o Change pulse duration **PULSE TIME = 200 us** (max. 200 μs)
    - o Scroll up and change **POWER** from **OFF** to **ON**

Reminder for switching the setup off;
- o Switch the plasma off
- o DC and pulsing unit
- o Oscilloscope and current probe
- o Magnetron cooling
- o Flow and flow controller unit

2.1.3 Discharge parameters

Student should investigate the influence of discharge power on the IEDF of Ar and Cr particles. For this purpose two discharges are compared. Discharge parameters for each discharge are given in the following table.

Parameter	unit	Discharge 1	Discharge 2
Pressure	Pa	0,3	0,3
Ar flow	sccm	72	72
Voltage	V	521	683
Peak Current	A	5	25
Frequency	Hz	100	50
Pulse duration	μs	200	200

Discharge power is elevated by increasing the voltage on the powers supply that consequently increases the current. By applying higher powers, higher thermal load is applied

to the target and in order to reduce the thermal load during discharge 2 frequency should be reduced.

Following images show expected discharge waveforms.
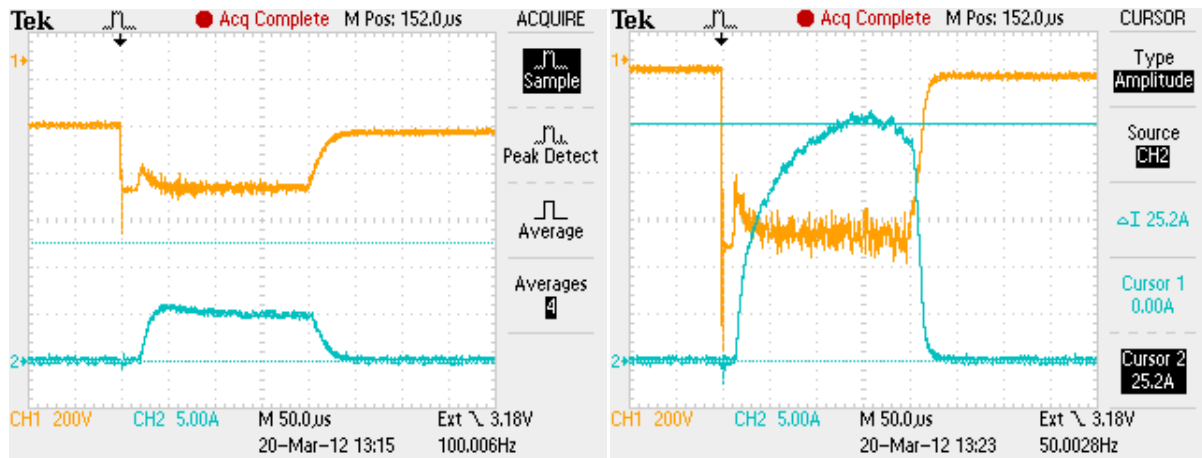
Discharge 1   Discharge 2

2.2 MassSoft

Templates for mass scan (Mass scan.exp), time averaged measurements (time averaged.exp) and for the time resolved measurements (time resolved.exp) can be found in the folder:

C:\Dokumente und Einstellungen\ep2\Eigene Dateien\Mass Spectrometer\EQP\Template\Student

Scan starts by clicking on to the green round button in the program menu.
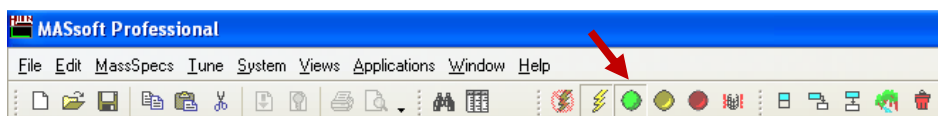
Scans can be exported to .csv file for plotting and analysis. Unfortunately, scans can be saved only one by one. Click on the scan you want to save and go to "File -> Export -> File" and save the scan. Repeat the steps for all scans.
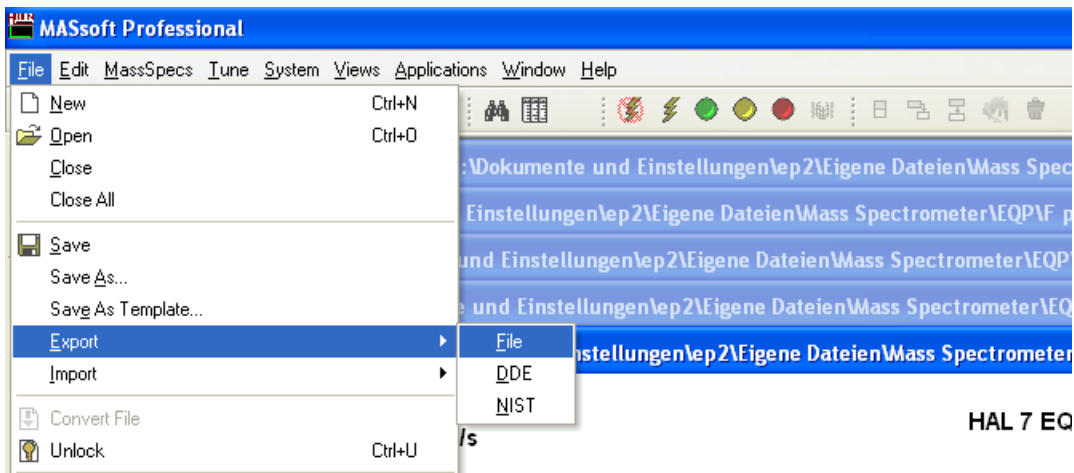
2.2.1 Mass scan

Typical Mass scan is shown in the following picture, recorded at energy of 2 eV, with strong peak at 40 amu representing Ar^+, and accompanying isotopes. Peak at 52 amu is Cr^+, peak at 20 amu is Ar^{2+} (m/q = 40/2) and small peak at 26 amu is Cr^{2+} (m/q = 52/2).
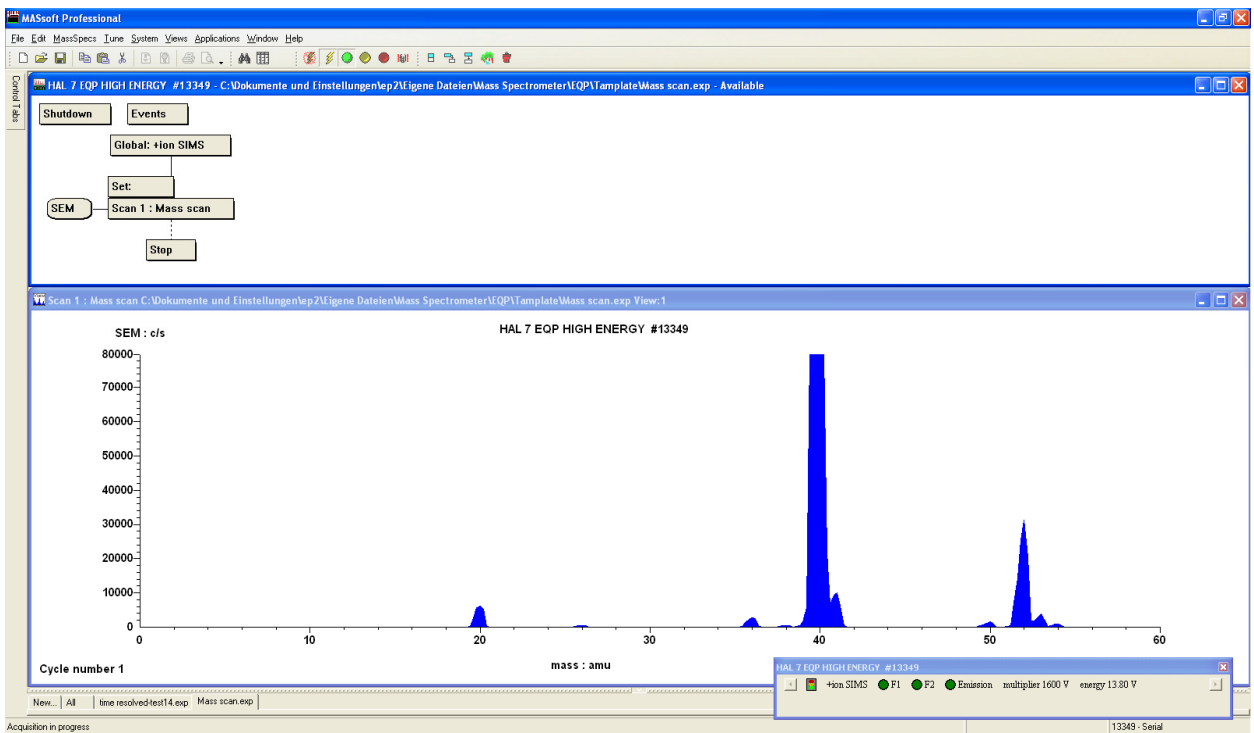
Mass scan performs scan at fixed energy that is usually a few eV since it is expected that majority of ions is thermalised and peak of the ion energy distribution function lays at 1 or 2 eV.

2.2.2 Time average energy scan

Typical Energy scan is shown in the following picture. The scan tree window contains four energy scans for Ar^+, Cr^+, Ar^{2+} and Cr^{2+}.
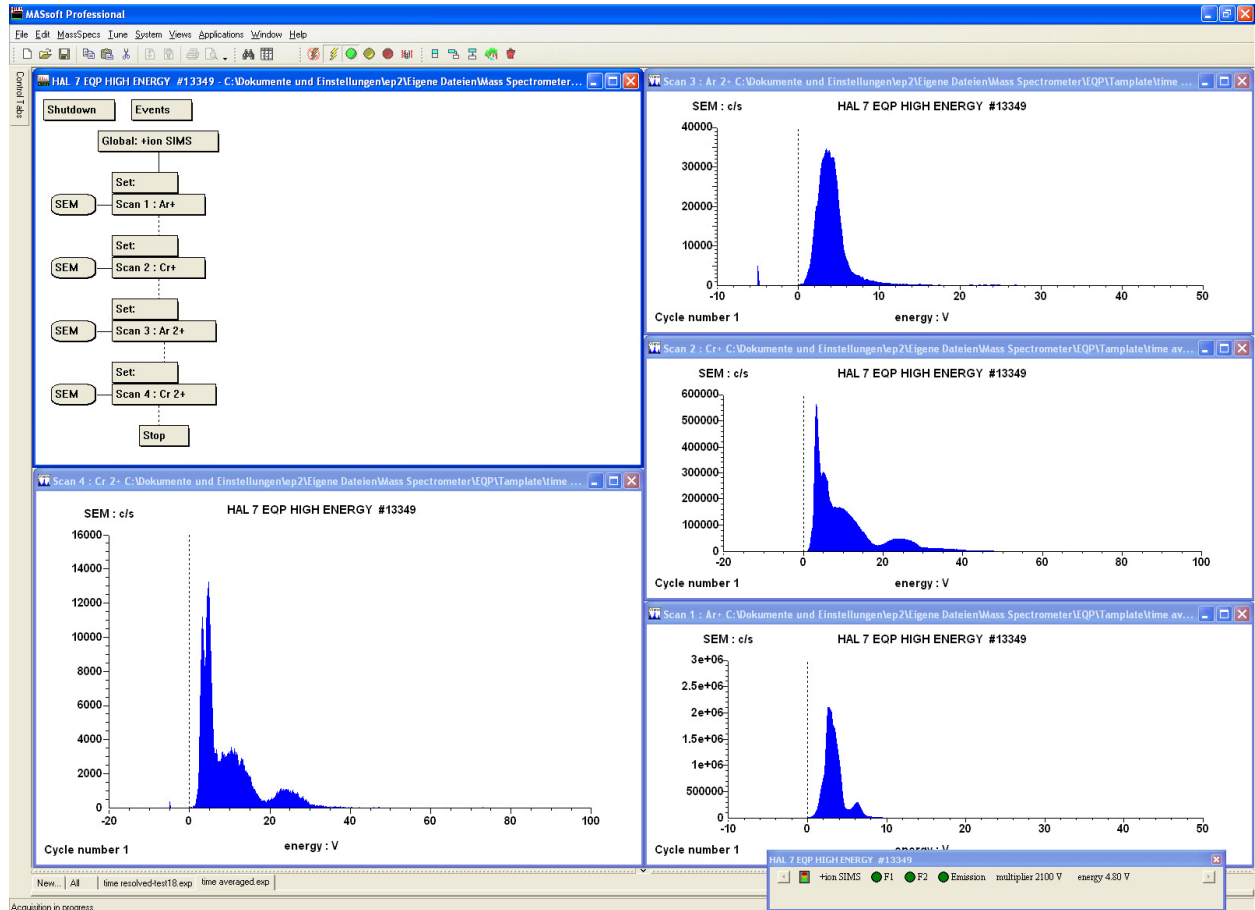

2.2.3 Time resolved energy scan

The time resolved measurements are same as the time averaged measurement with difference that measurements are triggered. Custom cable should be plugged in AUX I/O MSC-05 port at the back of the Mass Spectrometer Interface Unit on one side and the other BNC side should be plugged in the AB channel of the DG 645 Delay Generator.

The delay generator uses TTL signal from the power supply as a trigger and creates a new TTL signal where value set at the A edge sets the delay between the power supply trigger and new TTL signal, basically the desired time delay. Value at edge B is the width of a new TTL signal. The new TTL signal is used to trigger the Mass spectrometer detector. Minimum acquisition time at the detector is 1 ms. By setting the width of new TTL signal to 10 µs, meaning time resolution is 10 µs, the measurement will be accumulated over 100

pulses ($100 \times 10\mu s = 1$ ms). Consequently, setting the width to 20 µs the signal will be accumulated over 50 pulses.

2.3 DG 645 Delay generator
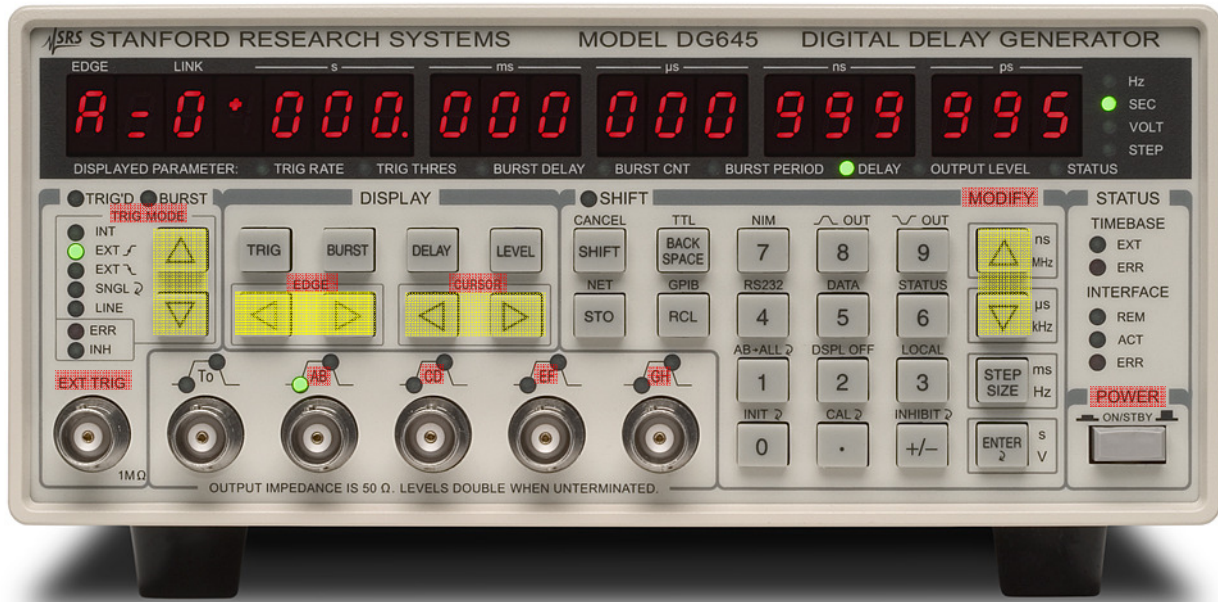
- Switch the power button on the right bottom side of the delay generator
- Connect external trigger and define the trigger edge by scrolling up and down with the arrows in the TRIG MODE
- Plug the cable for the new delayed trigger in either AB, CD, EF or GH channel
- Example: AB channel
  o Scroll EDGE until you reach A channel
  o To adjust the delay of the A edge use CURSOR to reach the digit you want to alter
  o Change the digit by increasing it or decreasing it in MODIFY menu
  o Now Scroll EDGE until you reach B channel to change width of the new channel
  o Use CURSOR to reach the digit you want to alter
  o Change the digit by increasing it or decreasing it in MODIFY menu
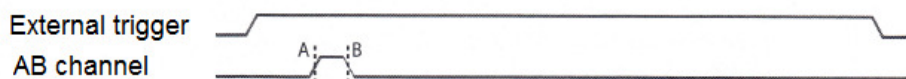
3. Exercises

The aim of the F praktikum is to perform characteristic measurements of the ions in plasma using mass spectrometer. The mass scan provides information on particles that can be found in the plasma by scanning over mass to charge ratio with fixed energy. Time averaged energy measurement performs a scan over energies for fixed mass to charge ratio resulting in the ion energy distribution function (IEDF). The scan accumulates the signal for 300 ms for each energy point. With pulse duration of 200 μs and repetition of 50 Hz and 100 Hz, the scan collects over 15 or 30 pulses depending on frequency. Meaning ions arriving both during the pulse and between the pulses are recorded and it represents the IEDF of ions arriving to the substrate where thin film is deposited. In order to understand the origin of different energy groups of the IEDF, time resolved measurements at points during the pulse, shortly after the pulse and in between the pulses is recorded. Furthermore the scans will be measured for two discharges in order to understand the influence of the power on the IEDF of Ar and metal ions.

The experimental part starts by venting the vacuum chamber and repositioning the magnetron in order to position it facing mass spectrometer at distance of 15 cm. Once the magnetron is mounted the chamber is pumped down to a base pressure of 5×10^{-6} mbar.

3.1 Mass scan

Goal:

Observe particles that are present in the HIPIMS discharge. Find most representable energy at which to conduct the mass scan.

Task:

Run the time averaged scan for discharge condition with 5 A to find the peak energy of the IEDFs. Recognise 2 peaks and perform mass scan for both peaks. Repeat the procedure for discharge condition with 25 A and extract the data into .csv file.

For report (Protokoll):

Recognise the ions from the mass scan, including associated isotopes. Discuss the intensities of Ar and metal ions, both for singly and doubly charge ions. Comment on the change of the intensities of the peaks for two scan energies. Comment on the change of the intensities when increasing discharge power.

3.2 Time averaged energy measurement

Goal:

Understand influence of discharge power on the shape and intensity of IEDF, and changes in the energy span.

Task:

Measure the IEDF of Ar^+, Ar^{2+}, Cr^+ and Cr^{2+} ions for two discharge conditions. Extract the data into .csv file and plot the data with aim to compare the IEDF of one species at different discharge powers.

For report (Protokoll):

Discuss relevant intensities and shapes of different species. Comment on the change of the IEDF when increasing discharge power. Integrating IEDF over the energy calculate the ion fluxes and plot them as a function of power.

3.3 Time resolved energy measurements

Goal:

Understand origin of different energy groups in the time averaged energy measurement.

Task:

Set parameters for discharge conditions with 25 A. Measure the IEDF of Ar^+, Ar^{2+}, Cr^+ and Cr^{2+} ions for three points in time, 220 μs, 380 μs and 600 μs. Extract the data into .csv file.

For report (Protokoll):

Plot time averaged measurements and time resolved measurement of each species on the same graph to recognise the origins of certain ion groups. Pay attention to the fact that acquisition lengths were different. Comment on the shapes of IEDF regarding the times it was measured and recognise Ar rarefaction enhancement. Discuss difference between Thompson and Maxwellian distribution. Explain the results taking into account Ar rarefaction and thermalisation of the particles

One third of the report should consist of introduction and two thirds should be description of your experiment and discussion of the results. Apart from the discussion relevant to the samples that you have investigated, you can use the following set of questions to help you shape your report:

- What is magnetron sputtering?

- What is HIPIMS?

- What are the main principles of the Electrostatic Quadrupole Plasma (EQP) Mass Spectrometer? What information can we obtain using the Mass spectrometer?

4. References

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