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Design and Development of a Chopper for Ion Beam Current Measurement and Monitoring

S.Shafiei*, M. Lamehi-Rashti, Y.Vosoughi

Physics and Accelerators Research School, Nuclear Science and Technology Research Institute, (NSTRI), P.O. Box:11365-3486, Tehran-Iran.

ABSTRACT

For the ion beam analysis of insulating materials, we have investigated the design and calibration of an ion beam chopper. The chopper consists of a holder, a chopper plate, four photo sensors, a stepper motor, and an electronic control unit. The chopper plate was designed based on sharing an equal fraction of the ion beam between the chopper and the target. The situation of the chopper to the ion beam is controllable by using four photo-sensors around it. The time intervals in which the material is analyzed and the number of incident ions measured are determined via gate pulses governed by the sensors' signals. The ion beam current was measured by charge integration at the chopper plate. We calculated the charge correction factors to eliminate the contribution of secondary electrons to the measurements. The measurements were done via Rutherford backscattering spectroscopy (RBS) analysis of a thin Au layer deposited on Si wafer with helium and proton ions in the energy range of 1–2.2 MeV with a precision of less than 5%. The charge correction factors are independent of the ion beam current.

Keywords: Ion Beam Analysis (IBA); Beam chopper; Ion beam current measurement; Charge integration; Ion beam monitoring.

I. Introductions

The Ion Beam Analysis (IBA) is a powerful analytical technique to obtain quantitative information about the composition and structure of a sample as a function of depth [1, 2]. This beneficial information is not acquired unless the precise knowledge of the number of probe ions on a target or the ion beam current is known. Therefore, employing a current measurement device in the IBA setup is crucial. IBA techniques are generally accomplished in a vacuum chamber with the ion beam current about the nano ampere. So, the Faraday cup is the only detector with the ability of intrinsic calibration that can be applied for the ion beam current measurement [3-6]. The Faraday cup is a post-sample current measurement method, so employing it depends on the target composition, thickness, and the target holder design. The isolating and the thick target and closed-back target holder, which avoid the ion beam reaching the Faraday cup, make it useless for the ion beam current measurement.

In conclusion, an alternative method for current measurement in the IBA experimental setup is necessary.

The charge integration at the sample is another way of ion beam current measurement [1]. This method is impractical in the case of an isolating target. Furthermore, the charge integration on the thin sample does not lead to an accurate, current measurement.

**Corresponding Author name:* S. Shafiei
E-mail address: sshafiei@aeoi.org.ir

Employing the Rutherford Backscattering analysis concurs with the intended IBA and is also a precise and confident method used for ion beam current measurement unless the experiment limits the use of the additional detector in the analysis chamber [7, 8].

It should be noted that the secondary electron suppression should be considered in all methods mentioned above, apart from the RBS analysis method, for precise ion beam current measurement. An ion beam chopper is the pre-sample current measurement method, which provides the correct measurement independent of the target characteristics and the target holder design [9-11]. The ion beam chopper has been constructed in the shape of wire, blade, and vanes, which rotates with a constant frequency and regularly cuts the ion beam. Then, the ion beam current is measured from the RBS spectrum of the ions from the chopper or the charge-integrating at its surface [12-17]. Since the chopper measures the part of the ion beam, the current measured by the chopper should be calibrated by a reliable device, such as a Faraday cup.

In this paper, the design and development of an ion beam chopper are presented for an IBA chamber in which many limitations appear. This chopper is considered an alternative current measurement method in the Rutherford backscattering-channeling (RBS-C) chamber. This chamber's primary current measurement method is integrating charges at the sample. During the isolation process, charges accumulate on the specimen, increasing the potential in the beam spot. The potential makes the beam spot shift on the target due to the electric field produced by the accumulated charges on the surface of the target. Subsequently, the RBS-C analysis is impossible. The electron beam flow toward the sample would neutralize it. Nevertheless, the problem of measuring the ion beam current is unsolved.

II. Principal of Measurement Methods

The target holder in the mentioned chamber is a closed-back so using the Faraday cup was useless. As the initial detector in this chamber can be positioned precisely at any angle toward the ion beam, employing the second detector to take advantage of simultaneously RBS analysis for current measurement would limit the initial detector motion. Accordingly, the ion beam chopper system was the only suitable way of ion beam current measurement in this chamber. The matters considered in the design of the chopper were simplicity, taking the least space, not interrupting the present facility and a permanent installation in the chamber. What makes this chopper distinctive from the ones that have been reported is that the position of the chopper to the ion beam axis (being in or off beam axis) is detectable and adjustable. This causes the intervals through which the ion beam current is measured, and the sample is analyzed determinable. It also monitors the ion beam before it enters the chamber by putting the chopper in the axis of the ion beam. The chopper was designed to receive an equal share of the ion beam by the chopper and the target. This feature leads to omitting the calibration stage. By considering the same number of intervals with equal duration for both positions of the chopper in and out of the ion beam axis, it is possible to normalize the RBS and RBS/C spectra of a sample to the same charge. This issue is important because the calculation of the channeling parameters from the channel spectrum needs the information on the cross-section of the reaction and the experimental setup parameters. This information is extracted from the experimental random spectrum [18, 19]. So, it is necessary to record the random and the channel spectra of a sample by considering the same number of impact ions to the target.

The secondary electron suppression system was not considered for the chopper. Thus, the chopper measures the ion beam current and secondary electron yield. The calculation of the correction factors excluded the contribution of these electrons in the measured ion beam current. The correction factors were calculated in the term of the right ion beam current divided by the measured one by the chopper. The suitable ion beam current was measured by the RBS spectrum of a thin Au layer deposited on the Si target. The calculations were done for the helium and proton ions in the energy range of 1–2.2 MeV. The dependency of the charge correction factors to the ion beam current was investigated.

III. Material and Methods

The ion beam chopper consists of a holder, a chopper plate, four transmission-type photo-sensors, a stepper motor, and an electronic control unit. The holder and the plate were made of aluminum. The schematic of the holder and plate are presented in fig. 1.

The chopper is placed at the beam transport tube entrance to the chamber. The holder is 98 mm in diameter with a hole in its center of 10 mm. The center of the holder is along the axis of the ion beam transport–tube. The ion beam enters the chamber through this hole. The stepper motor is placed underneath the central hole of the chopper holder (see fig.1). The chopper holder is fixed at the chamber entrance using four cam-screws around it. The chopper plate is a disc of 54 mm in diameter with two empty arcs with a central angle of 90°, located opposite each other. The arcs are 4 mm in width, and its inner radius is 16 mm from the center of the plate. The times the beam current is measured (T_{ch}) and a sample is analyzed (T_T) are equal. The chopper plate interrupts the ion beam two times in each turn.

Four optocoupler photoelectric sensors are positioned around the chopper plate to identify the position of the chopper to the ion beam. The sensors are placed around the chopper at the points numbered in fig.1. The sensors are fixed on the chopper holder by Aluminum fastening. Two holes of 1 mm in diameter facing each other are near the edge of the chopper plate through which the light of the emitter of the photoelectric sensors reaches their receiver, and signals are produced in the terminals. When the chopper rotates, one of the holes passes through the sensor numbered 1, and a signal is produced. This signal indicates the beginning of the T_T. Then, the other hole passes through the sensors numbered 2. The signal produced at the terminal of this sensor indicates the end of the T_T. Next, the hole passes through the sensor numbered 3 and 4, and signals that show the beginning and end of the T_{ch} are produced. The T_{ch} and T_T are specified by a corresponding logic pulse according to the sensors' signals. These logic pulses are shown in fig.2a.

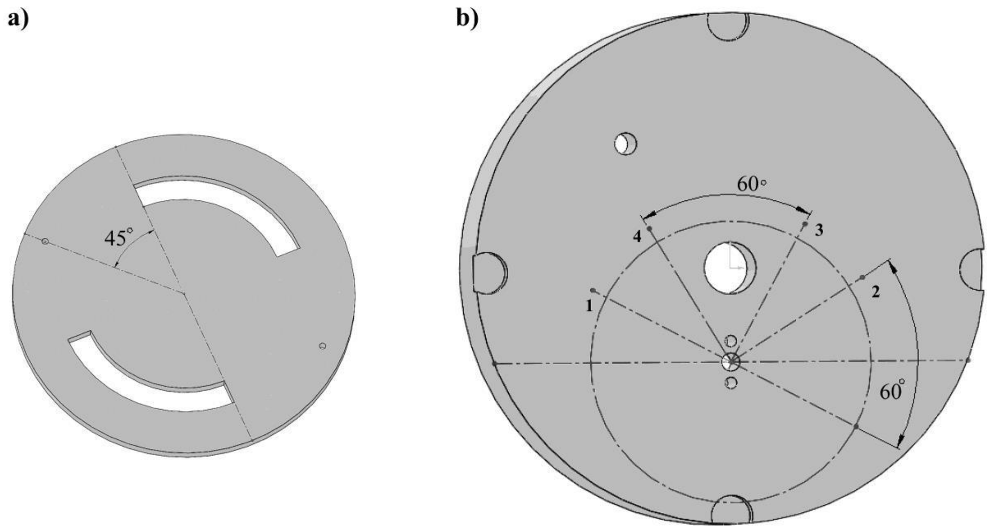

Fig. 1 the schematic of a) the plate and b) the holder of the ion beam chopper.

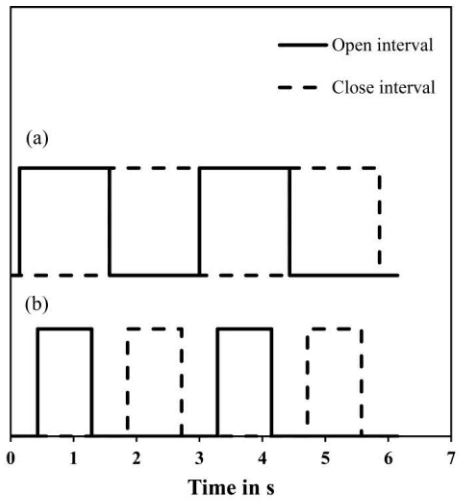

Fig. 2 the extracted logic pulses from the signals of the sensors a) include and b) exclude the open edges.

It is evident that when the ion beam impacts the edges of the open arcs on the chopper plate, some ions hit the chopper, and others pass through it. As a result, the number of ions is scattered from the edges of the open arcs. If such scattered ions reach the detector, it will cause background in the target spectrum. To omit this background, the sensors were placed so that the times the ion beam hits the edges of empty arcs on the chopper plate are removed in the width of the produced logic pulses (see fig.2b). As shown in fig.1, the angle between the two sensors indicating the open or closed position of the chopper is less than 90°.

The step motor is connected to a power supply and turns the chopper plate with a frequency of 9 RPM. The stepper motor and the chopper base are insulated toward each other. The ion beam current is measured via charge integration at the chopper plate through the motor shaft during the T_{ch}.

The RBS or RBS-Channeling spectrum of the sample is also measured during the T_T.

The ATxmega64a3u microcontroller was used in the electronic controller unit. The controller unit consists of four buttons, three BNC terminals, and two LEDs.

Four buttons set the chopper plate to four states, the open, closed, rotation, and stop states, to the ion beam by considering the signals of these sensors. The open state allows the permanent installation of the chopper in the chamber. The close state enables the chopper to monitor the ion beam before entering the chamber. The first BNC terminal allows ion beam current measurement directly from the chopper plate. This BNC is connected to a current digitizer unit to measure the number of ions hitting the chopper. The second BNC supplies logic pulses with widths equal to T_T. The third BNC supplies logic pulses with widths equal to the T_{ch}. The logic pulses supplied by the second and third BNC are used as gate pulses for the ADC recording the target spectrum and the current digitizer. Two LEDs turn on, corresponding to the second and third BNC terminal. Since the T_T and T_{Ch}, are not simultaneous, the chopper was programmed to turn 50 rounds by pushing the start button. Therefore, 100 gate pulses will be produced for each open and closed interval in each run.

The number of ions hits on the chopper is expected to be equal to the one that impacts the target. The only differences would be2 caused by secondary electron emission from the chopper or less likely, by misalignment of the sensors. The contribution of such err. one measurement was obtained via calculating the correct current by the Rutherford backscattering of a thin layer. The schematic of the RBS set-up is shown in fig.3.

A Si wafer on which a thin Au layer was deposited was used as a target. the Au layer was deposited by the sputtering. The Au thickness was calculated at 6 nm by the RBS analysis. The Si surface barrier detector with a radius of 5 mm was employed at the angle θ=165° to the incident beam. The distance between the target and the detector is about 111mm. The energy resolution of the detection system is 15 keV. RBS analysis was done using helium and proton ion beam produced by a 3 MeV Van de Graaff accelerator over the energy range of 1–2.2 MeV in the step of 200 keV.

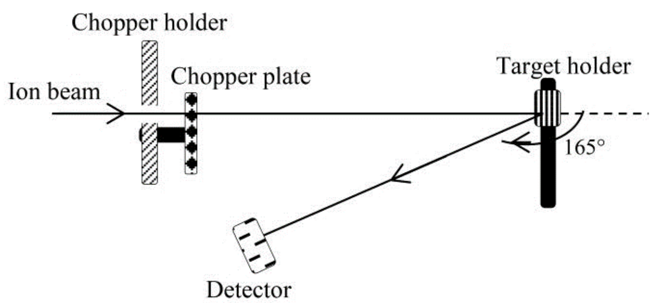

Fig.3 the schematic of RBS set-up used for the current correction.

Then, the spectra were simulated by SIMNRA code [20] to find the correct number of incident ions on the target (N_T). The charge on the chopper was measured concurrently with RBS analysis. Then, it was converted to the number of incident ions on the

chopper (N_{Ch}) by knowing the solid angle of the detector. The charge correction factor in each ion beam energy was calculated from the ratio of the N_T to N_{Ch}. The measurement of each energy was repeated five times. Finally, the dependency of the charge correction factor on the ion beam current was investigated.

IV. Result and Discussion

The beam chopper mounted at the entrance of the ion beam transport – tube to the chamber is shown in fig. 4.

The electronic control unit is illustrated in fig. 5.

The first BNC on the right is used for ion beam current measurement.

The charge correction factors for helium and proton ions in the range of 1–2.2 MeV are shown in fig.6. The dashed lines are drawn to guide the eye. The correction factors indicate how much they charge on the sample is less than the one measured by the chopper. When the chopper measures the current, these factors should be considered concerning the energy of ions. It is known that the secondary emission is responsible for the discrepancy between the charge on the sample and the one on the chopper. The secondary electron yield is proportional to the stopping power [21]. Furthermore, the stopping power of an ion is a function of m/E [22]. Subsequently, the secondary electron yield drops by climbing up the ion beam energy and decreasing the ion mass. So, the secondary electron yield drops by climbing up the ion beam energy and diminishing the ion mass.

Fig.6 illustrates that the charge correction factor grows by increasing the ion beam energy and decreasing the mass of the ions.

Of note, for the He ions, the number of incident particles on the target was calculated by considering the singly charged helium ions.

The statistical error in the calculation of the incident ions from the RBS spectrum originates from the uncertainties in the determination of the solid angle of the detector (0.6%), Au layer thickness (0.6%), and differential scattering cross-section (1% for the helium ions and 2% for the protons ions). The Rutherford cross-sections were considered for the reactions of helium and protons in Au. The non-Rutherford cross-sections were used for the responses of the protons with an energy greater than 999keV in the Si. For the protons with an energy less than 999keV and He in all energy, the Rutherford cross-sections were employed. The number of detected ions is high enough, so the uncertainty due to ion counting is negligible. Repeating the measurement in each energy revealed that the uncertainty in the number of incident ions measured by chopper was less than 4%. As a result, the accuracy of the calculated charge correction factor is less than 5%.

To investigate the effect of the ion beam current on the charge correction factor, the charge correction factor for the helium ions in the energy of 2 MeV was calculated for the ion beam current of 7.5 nA, 15 nA, and 30 nA. The dependency of the charge correction factor on the ion beam current is illustrated in fig.7.

fig.7 shows that the charge correction factor is independent of the ion beam current in the range of ions current used for IBA. The result is consistent with the other reference [15].

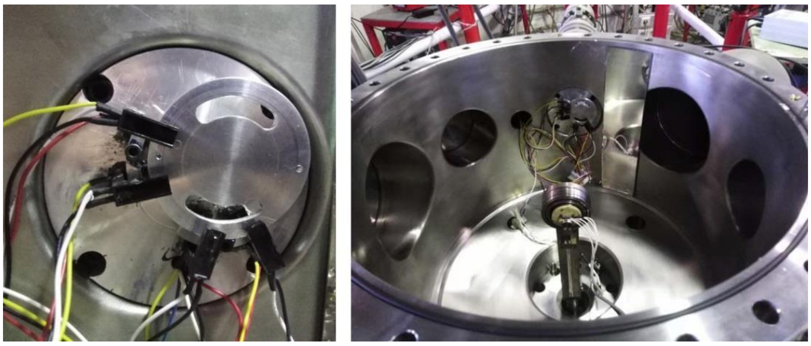

Fig. 4 the beam chopper mounted on the chamber.

Fig. 5 the electronic control unit of the beam chopper.

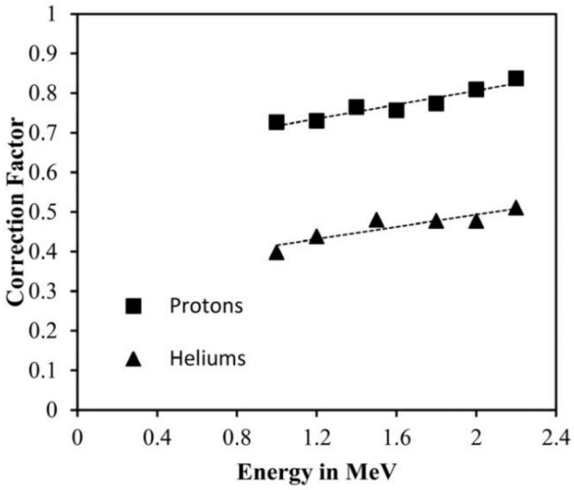

Fig.6 the charge correction factor for incident helium and proton particles in the range of 2.2 MeV.

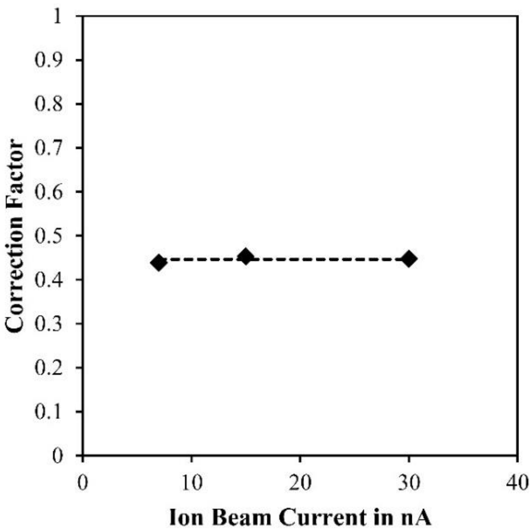

Fig.7 the charge correction factor of 2 MeV helium ions with a current of 7.5 nA, 15 nA, and 30 nA.

V. Conclusions

In this paper, an ion beam chopper was designed and developed to analyze the RBS-channeling of an isolated specimen. By considering the constraints imposed by the experimental set-up, the ion beam current was measured by integrating the charge at the chopper surface. This chopper aims to measure the ion beam current and provide the necessary condition for RBS-C analysis. The condition records the random and channel spectra with the same incident ions on the sample. The equal number of opened and closed periods with the same duration in each run provides what is needed for analysis. Therefore, the channel parameters can be obtained by taking into account the information of the random spectrum. Besides, a comparison of the sample spectra along various planar and axial channels is possible.

Controlling the position of the chopper to the ion beam by using four photo-sensors around the chopper makes other advantages. The technique eliminates the background in the sample spectrum caused by the scattered ions from the open and closed segments of the chopper. Furthermore, adjusting the chopper to the closed position makes it an ion beam monitor. Hence, it is possible to set an ion beam current as intended after the ions pass through the beamline slits before reaching the target. Putting the chopper in the open position eliminates the chopper from the experimental set-up. Although the chopper was not equipped with secondary electron suppression, measuring the correction factor solved this problem. It can be said that this chopper was designed in a way that the calibration stage is replaced with the correction stage.

The charge correction factors for helium and proton ions in the range of 1–2.2 MeV were calculated. It is enough to multiply this data (corresponding to the energy of the ion beam) by what is measured by the chopper to find the ion beam current of each analysis.

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