Novel Faraday cup for the simultaneous observation and measurement of ion-beam currents

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A novel Faraday cup is described which allows the simultaneous observation and measurement of ion-beam currents. The Faraday cup is constructed around a Galileo channel electron multiplier array (CEMA), which serves as the basis of an internal image intensification system (a gain of $>10^5$) for the observation of the ion beam; the CEMA also acts as a collector for the ion current which is measured by a Keithley 602 electrometer. The ion current is integrated by a simple and inexpensive dosimeter; the electronic circuit for the dosimeter is described. The application of the Faraday cup to the observation and measurement of a 30-keV Ar$^+$ ion beam is presented as an illustrative example. We have also employed this Faraday cup to observe and measure 30-keV Cr$^+$, Mo$^+$, or W$^+$, and 18-keV Au$^+$ ion beams employed for the in situ irradiation of field-ion microscope specimens.

I. INTRODUCTION

For the past few years we have employed energetic (~10–45 keV) positively charged metal ion beams to irradiate metal field-ion microscope (FIM) specimens. The irradiations have been performed in situ under ultra-high vacuum [~(0.2–2) × 10$^{-9}$ Torr] conditions in a stainless steel FIM. The FIM specimen is attached to the tail of a continuous-transfer liquid helium cryostat via a copper FIM specimen holder that is clamped to a sapphire piece that serves to electrically isolate the specimen holder from the cryostat. The main problems with the in situ irradiations were the alignment and observation of the ion beam with respect to the FIM tip and the accurate measurement of the ion dose. Prior to the use of the design described in this paper we had employed a phosphor screen to first align and observe the ion beam and then a separate Faraday cup to measure the ion dose. This arrangement had the following deficiencies: (1) it was cumbersome; (2) it was time consuming; and (3) the photon yield per incident heavy ion on the phosphor is small, making it difficult to visually observe a heavy-metal or gas ion-beam (e.g., 30-keV Ar$^+$, Cr$^+$, Mo$^+$, or W$^+$).

To correct these problems we have designed and constructed a Faraday cup which allows us to both continuously and simultaneously monitor the ion-beam cross section and ion dose. At the heart of the present system is a Galileo channel-electron multiplier array (CEMA) which serves as the basis of an internal image intensification system to observe the ion beam and also as an ion-beam collector in the Faraday cup. This design overcomes the major problem inherent to a conventional Faraday cup design, i.e., the inability to simultaneously observe the profile of the ion beam and to measure the ion dose. The present paper describes this novel Faraday cup which corrects the above mentioned problem. In addition, a simple dosimeter is described which gives a direct readout of the integrated flux (i.e., the dose). The use of this Faraday cup to measure and observe an ion current of 2 × 10$^{-9}$ A of 30-keV Ar$^+$ ions is presented as an illustrative example of the capabilities of the present design. In addition, we have also used the present design to observe and measure 30-keV Cr$^+$, Mo$^+$, or W$^+$, and 18-keV Au$^+$ ion beams during the in situ irradiation of tungsten FIM specimens. There appears to be no fundamental limitation on the application of this design to the observation and measurement of all the elements in the periodic table that one can make into positively or negatively charged ion beams.

II. DESIGN AND PERFORMANCE OF THE FARADAY CUP

A. Faraday cup and the channel electron multiplier array

Figure 1 shows a cross-sectional top view of the Faraday cup (right-hand side) and its relationship to the FIM specimen (left-hand side). The FIM specimen is in the form of an ~1-cm-long wire (~0.13–0.20 mm in diameter) which is sharply pointed and is mounted on a hexagonal-shaped copper FIM specimen holder. The FIM specimen and its holder are surrounded by a cylindrical copper thermal radiation shield which contains two apertures; the first aperture defines the cross-sectional area of the ion beam that impinges on the FIM specimen. The second aperture is made larger in diameter than the first one to avoid an ion-beam shadowing effect. In addition, a piece of gold metal is attached to the cylindrical thermal copper radiation-shield on the side of the first aperture to further shield the Faraday cup from any portion of the ion beam which may accidentally bypass the first aperture.

The ion beam that passes through the second aperture of the cylindrical copper thermal radiation-shield
next enters the Faraday cup as it passes through an annular stainless steel ring that served as a secondary-electron retarder; the latter is biased at \(-300\) V dc. The secondary-electron retarder prevents electrons that are produced inside the secondary-electron collection cylinder, floating at 0 V, from escaping from the Faraday cup, and it also prevents stray electrons from entering the Faraday cup. The long stainless steel secondary-electron collection cylinder serves to recapture any secondary electrons that are released by the ion beam. Finally, the ion beam is collected on the front surface of the CEMA, which is also floating at 0 V, and it is measured with a Keithley 602 electrometer. The incident ion-beam current is also converted to an electron current by the CEMA. The back surface of the CEMA is maintained at \(+900\) V dc; the voltage drop of 900 V dc across the CEMA produced a gain of \(\approx 10^9\). The CEMA is separated from a P-1 phosphor screen deposited on a glass plate, by a 1.6-mm-thick annular ring fabricated from Corning No. 2598 machinable glass.

The electron current produced by the CEMA is accelerated and proximity focused onto the phosphor screen which is maintained at \(+1500\) V dc. The glass plate, on which the phosphor is deposited, is coated with a conducting layer of tin oxide. The visible light given off by the phosphor is observed through an \(\sim 2.5\)-cm-diam glass window on the FIM. An example of the observational capability of the CEMA portion of the Faraday cup is shown in Fig. 2. Figure 2(a) shows the cross-sectional image of a 30-keV Ar\(^+\) ion beam at a current density of \(4 \times 10^{-9}\) A cm\(^{-2}\). Figure 2(b) shows an FIM specimen which was biased at \(\sim 600\) V dc to give a shadowgraph of the tip in the ion beam; this technique has been found to be extremely useful for rapidly aligning the FIM specimen with respect to the ion beam.

**B. Measurement of the positive ion current**

The problem of measuring the total ion current \(I_i\) is best explained with the aid of the approximate equivalent circuit, shown in Fig. 3, for the irradiation system and the Faraday cup. The numbered points 0 to 3, at the top of the circuit, correspond to the secondary-electron retarder (0), the front surface of the CEMA (1), the back surface of the CEMA (2), and the phosphor screen (3). The total ion current enters the Faraday cup at the point 0 from the irradiation system; the diode used in the irradiation system portion of the diagram indicates symbolically that a reverse positive-ion current is not possible in this portion of the circuit. The quantity \(I_i\) can divide itself into three separate ion currents \(I_{i1}, I_{i2},\) and \(I_{i3}\) at the points 1, 2, and 3 respectively; in general it is expected that \((I_{i2} + I_{i3}) \ll I_{i1}\). The ion currents \(I_{i1}, I_{i2},\) and \(I_{i3}\) rejoin at point F and flow through the Keithley 602 electrometer. The electron current in the loop 1, 2, 3, \(V_{i1}, V_{i2},\) and \(F,\) denoted \(I_e,\) is not measured by the electrometer whereas the leak-

![Fig. 2. (a) A photograph of the image of a 30-keV Ar\(^+\) ion beam with the FIM tip at earth potential; the current is \(2 \times 10^{-9}\) A on an area of 0.5 cm\(^2\). (b) In this case the FIM tip is at a potential of \(+600\) V dc, and the shadow of the conically shaped tip is readily seen; same Ar\(^+\) ion current. Both images were recorded on Polaroid 3000 ASA film.](image-url)
Since an important physical quantity, for every irradiation, is the total dose (i.e., the integrated flux), a simple and inexpensivedosimeter was constructed to integrate the $I_1$ with respect to time.$^{17}$ The Keithley 602 electrometer converts $I_0$ to an equivalent voltage ($V_{in}$); this electrometer provided an output voltage of 1 V dc for full-scale meter deflection on any current range.

Figure 4 shows the schematic diagram for the dosimeter which is essentially an analog integrator. An adjustable voltage source is connected to the non-inverting input of the difference amplifier to diminish the self-integration of the integrator to less than 10 $\mu$V s$^{-1}$. The multiplier stage is used to calibrate the output voltage ($V_{out}$); the quantity $V_{out}$ is given by the equation

$$V_{out} = \beta \int V_{in}(t)dt,$$

where $\beta$ is an adjustable constant with the dimensions of s$^{-1}$.

Let us now consider an example of how Eq. (2) was used in practice. The object was to obtain a value of $V_{out}$ which was proportional to the total dose. For example, for $I_0 = 10^{-9}$ A, an irradiation time of 600 s and an ion-beam cross-sectional area of 0.5 cm$^2$ the dose was $0.75 \times 10^{12}$ ion cm$^{-2}$. Thus we calibrated the dosimeter to obtain $V_{out} = 0.75$ V dc. For $I_0 = 10^{-9}$ A the value of $V_{in}$ was 0.33 V dc using the $3 \times 10^{-9}$ A range on the electrometer; therefore, employing Eq. (2),

$$V_{out} = 3.75 \times 10^{-3} \int V_{in}(t)dt$$

for this scale of the electrometer and for the cross-sectional area of 0.5 cm$^2$; we note that $I_0$ need not be constant for Eq. (2) to be valid. The dosimeter can, of course, be calibrated in a similar manner for any other ion-beam cross-sectional area or current scale of the electrometer. The dosimeter was found to be particularly useful in terminating the ion irradiation at some predetermined dose.

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III. SIMPLE DOSIMETER

The current $I_0$, which is essentially equal to the quantity $I_1$, is measured by a Keithley 602 electrometer.
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9 C.-Y. Wei and D. N. Seidman, Cornell Materials Science Center Report #2398 (1977); submitted for publication (1977).
12 The total cross-sectional area of the ion beam was 0.5 cm²; therefore, the area occupied by the FIM specimen only represented ~1% of ion-beam's cross-sectional area.
14 The Sylvania No. 160 phosphor (P.1) is a Zn₂SiO₄ : Mn material which has a fluorescent and phosphorescent color in the green; it is a medium persistence phosphor.
17 For example, see Linear Applications (National Semiconductor Corp., Santa Clara, CA, 1973), p. AN31-1 for a description of the operational amplifiers used in the dosimeter circuit.